UNION GÉODÉSIQUE ET GÉOPHYSIQUE INTERNATIONALE
INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

ASSOCIATION INTERNATIONALE
D'HYDROLOGIE SCIENTIFIQUE

INTERNATIONAL ASSOCIATION
OF SCIENTIFIC HYDROLOGY

COLLOQUE DE HANNOVERSCH-MÜNDEN

8—14 SEPT. 1959

SYMPOSIUM OF HANNOVERSCH-MÜNDEN

TOME I — VOLUME I
EAU ET RÉGIONS BOISÉES
WATER AND WOODLANDS

PUBLIÉ AVEC L'AIDE FINANCIÈRE DE L'UNESCO

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SECRÉTAIRE : L. J. TISON
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DIE INTERCEPTION IN BUCHEN- UND FICHTENBESTÄNDEN; ERGEBNIS MEHRJÄHRIGER UNTERSUCHUNGEN IM ROTHAARGEBIRGE (SAUERLAND)

von FRANZ ERICH EIDMANN

ZUSAMMENFASSUNG

Die Ruhr, ein kleiner Nebenfluß des Rheins, hat eine überragende Bedeutung als Wasserlieferant für das bedeutendste Industriegebiet Europas. Der Bedarf der Industrie und der sehr dichten Bevölkerung dieses Gebietes ist ständig im Steigen und beträgt heute 1,3 Mrd. cbm im Jahr. Er konnte bisher auch in Trockenjahren gedeckt werden, da das Einzugsgebiet der Ruhr (4500 qkm) im niederschlagsreichsten Mittelgebirge Deutschlands liegt (1000 mm im Jahr). Dieses ursprünglich mit Buchenwald bestockte Gebirge hat seinen Waldcharakter entscheidend geändert durch rasch fortschreitende Umwandlung der Buchenbestände in reine Fichtenforste. Zur Klärung der Frage, ob zwischen Buchen- und Fichtenbeständen ein wesentlicher Unterschied hinsichtlich der Spende an nutzbarem Wasser besteht, wurden im Kerngebiet des Gebirges 28 Versuchsflächenpaare in je einem benachbarten Buchen- und Fichtenbestand angelegt. Im 5jährigen Mittel aller Versuchsflächen betrug die Menge des durch die Krone getropften Niederschlags bei Buche 75,6 %, bei Fichte 73,3 % des Niederschlags im Freiland (Tab. 1).

Außerdem wurde der Stammabfluß an jedem Stamm einer Buchen- und Fichtenfläche gemessen. Er betrug bei Buche 16,6 %, bei Fichte 0,7 % des Niederschlags (Tab. 2 und 3). Unter Berücksichtigung dieses Stammabflusses betrug die Interception bei Buche im Jahresmittel nur 7,6 %, bei Fichte dagegen 25,9 % (Tab. 5). Von dem mittleren Jahresniederschlag von 1216 mm sind im Buchenwald 1123 mm auf den Boden gelangt, im Fichtenwald dagegen nur 902 mm.

SUMMARY

The effect of European Beech and Norway Spruce forests on the amount of precipitation reaching the ground has been object of investigations made in the Sauerland mountains (Western Germany) during 5 years. Measurements in 26 Beech stands and 30 Spruce stands involved a comparsion of the catch of rain or snow under the crowns with that in the open area. In each stand two or more randomly located gages were used. Precipitation in the open was measured with 10 gages paired with 10 different groups of stands in the nearest area. Stem flow has been measured by placing rubber collars around the stems of 23 Beeches and 28 Spruces.

In the 5 years period the mean catch of precipitation in rain gages under Beech forests has been 75,6 % of the precipitation in the open, under Spruce forests 73,3 % (Table 1). Percentage of stem flow in relation to precipitation has been 16,6 % for Beech and 0,7 % for Spruce (Tables 2 and 3). The percentage of net interception reached 7,6 % for Beach and 25,9 % for Spruce (Table 5). The mean annual precipitation of the area has been 1216 mm. In the Beech forests 1123 mm reached the ground, in the Spruce forests 902 mm only, which is a difference of 221 mm in favour of the Beech.

1. ANLASS ZU DEN UNTERSUCHUNGEN

Die Ruhr, ein kleiner Nebenfluß des Rheins, hat eine überragende Bedeutung als Wasserlieferant einer gewaltigen Industriezusammenballung. Das Einzugsgebiet der Ruhr, das rund 4500 km² groß ist, liegt zum weitaus größten Teil in den sehr niederschlagsreichen Mittelgebirgen des Sauerlandes. Im lang-

jährigen Mittel fallen in dem Einzugsgebiet 1000 mm Niederschlag, die rd. 4500 Mio m^3 Wasser liefern. Davon gehen etwa 2000 Mio m^3 durch Verdunstung verloren, so daß jährlich etwa 2500 Mio m^3 an nutzbarem Wasser zur Verfügung stehen. Der Wasserverbrauch in dem Gebiet ist seit Jahren vor allem durch den hohen Anteil des Industrieverbrauchs ständig im Steigen und steht heute etwa auf 1300 Mio m^3 im Jahr. Der Überschuß des Angebots scheint zunächst noch recht hoch. Wenn man aber bedenkt, daß das Angebot trotz des im allgemeinen ausgeglichenen semimaritimen Klimas dieses Landes um den annähernd dreifachen Betrag schwanken kann (1400—4000 Mio m^3 je Jahr), während der Verbrauch mindestens konstant ist und gerade in warmen, niederschlagsarmen Jahren über das Normalniveau steigt, so wird klar, daß Höchstverbrauch und Mindestangebot sich bereits bedenklich nahe stehen und Mangellagen in den Bereich der Möglichkeit rücken. Obwohl natürlich einer Beeinflussung der Höhe des zum Abfluß gelangenden Anteils des Niederschlags enge Grenzen gezogen sind, müssen angesichts der geschilderten Situation alle Faktoren untersucht werden, welche diesen Anteil beeinträchtigen, und dies insbesondere dann, wenn ein bestimmter Faktor einer ständigen einseitigen Änderung unterliegt. Dies ist im Sauerland der Fall, da der das Land auf 60 % der Gesamtfläche bedeckende Wald unter dem Einfluß der Wirtschaft sich in seiner Zusammensetzung grundlegend wandelt.

Das rechtsrheinische Schiefergebirge, zu dem das Sauerland gehört, war trotz seiner Höhenunterschiede von 300 bis 700 m ursprünglich ein reines Laubholzgebiet, in dem die Baumart Buche sehr stark vorherrschte, während nur in den unteren sonnseitigen Hanglagen auch die Eiche eine wesentliche Rolle spielte. Diese einstige Bestockung des Landes hat durch die menschliche Tätigkeit wesentliche Veränderungen erfahren. Schon im Mittelalter setzten durch die wachsende Bevölkerung Waldverwüstungen durch Viehweide, Streunutzung und Köhlerei ein, die wohl die Nutzholztauglichkeit der Wälder, weniger aber ihren wasserwirtschaftlichen Wirkungsgrad veränderten, da die Baumartenzusammensetzung etwa gleich blieb und eine längere Brache infolge der natürlichen Regeneration des Waldes kaum vorkam. Später wurde allerdings durch den Holzbedarf der Industrie vor allem in den Kreisen Siegen und Olpe die Eiche auf großen Flächen einseitig begünstigt, da bei rasch aufeinanderfolgenden Nutzungen die Eiche eine größere Ausschlagkraft als die Buche besitzt und sich daher schließlich allein behauptet. Aber auch in den so entstandenen umfangreichen Eichen-Niederwaldungen dürfte die wasserwirtschaftliche Situation sich gegenüber der vorher vorhandenen Bestockung kaum grundlegend verändert haben.

Eine entscheidende Wandlung brachte dagegen die starke Einwanderung der Nadelbaumart Fichte, die vor etwa 100 Jahren durch die planmäßige Umwandlung ertragsarmer Laubwaldflächen in Gang kam und später vor allem nach dem Erliegen der Eichen-Niederwaldwirtschaft ein enormes Tempo gewann. Heute besteht etwa die Hälfte der Wälder im Einzugsgebiet der Ruhr aus künstlich begründeten reinen Fichtenbeständen. Das Ende dieser Bewegung ist noch nicht abzusehen, da der wirtschaftliche Vorteil der Fichtennachzucht — vor allem im Kleinwaldbesitz — allzu sehr auf der Hand liegt. Es ist vorauszusehen, daß der einstige Laubwald des Sauerlandes in weiteren 100 Jahren auf verschwindend kleine Reste (vorwiegend im Staatswald) zusammengeschmolzen sein wird.

Das Ausmaß dieser völligen und ganz einseitigen Strukturveränderung der Vegetation wird noch dadurch erheblich gesteigert, daß durch die schlechte Ertragslage der Landwirtschaft, zumal auf den geringwertigen Böden des Sauerlandes, eine erhebliche Aufforstung mit der leicht und billig zu kulti-

vierenden und frühzeitig Erträge versprechenden Fichte eingesetzt hat. Die jährliche Zunahme der Fichtenwaldfläche allein aus diesen Aufforstungen armer Weiden und schlechter Äcker wird zur Zeit in Westfalen auf 1000 ha geschätzt.

Angesichts dieser Entwicklung lag die Notwendigkeit einer Untersuchung des Unterschiedes in der wasserwirtschaftlichen Bedeutung von Buchen- und Fichtenbeständen auf der Hand. Es mußten vor allen Dingen die Unterlagen für eine quantitative Aussage über die zu erwartende Auswirkung der Bestockungsveränderung auf die Abflußspende an nutzbarem Wasser gewonnen werden. Untersuchungsergebnisse über den Einfluß des Waldes ganz allgemein auf den Wasserhaushalt liegen aus der ganzen Welt — neuerdings auch aus Deutschland — vor; auch über die spezifische Wirkung verschiedener Holzarten waren und sind zahlreiche Arbeiten im Gange, leider jedoch in ganz anderen, vorwiegend kontinentalen Klimabereichen. Die besonderen Verhältnisse bei Buchen- und Fichtenbeständen im Einzugsgebiet der Ruhr mußten daher durch eine neue Beobachtungsreihe geklärt werden. Die Untersuchungen begannen mit dem Wasserwirtschaftsjahr 1951 (November 1950) und dauern noch an. Als Untersuchungsgebiet wurde das standörtlich typische und hinsichtlich der Arbeitsorganisation günstige Staatsforstrevier Hilchenbach gewählt.

2. Das Untersuchungsgebiet

Der Staatsforst Hilchenbach liegt im Rothaargebirge an der Ostgrenze des Kreises Siegen, etwa zwischen 400 und 680 m über NN. Sein Gebiet hat die Form eines in der Richtung NNW—SSO langgestreckten Rechtecks von etwa 20 km Länge und 8 km Breite.

Der im Bereich des Staatsforstes nord-südlich streichende Rumpf des Gebirges fällt nach Westen mit eingetieften Bachtälern verhältnismäßig steil ab. Der östliche Teil des Untersuchungsgebietes dagegen liegt auf dem breiten Rücken des Gebirges, der durch ein flachwelliges Gelände mit nur wenig eingetieften Tälern und flachen Kuppen charakterisiert wird. Die Bäche entspringen meist in weiten und oft vernäßten, teilweise sogar vermoorten Mulden. Diese Hochfläche wird durch die Eder und die Lahn entwässert.

Das Gebirge wird aufgebaut aus meist schiefrigen Grauwacken, die teilweise mehr sandig, teilweise schluffig-tonig sind. Der Gehalt an verwitterbaren Mineralien in den Gesteinen des Unterdevons ist gering und nur wenig wechselnd. Infolge der hohen Niederschläge und niedrigen Sommertemperaturen sind die Böden besonders in den oberen Horizonten nur gering basenhaltig. Die Quellen treten meist an den Grenzflächen von wasserführenden Grauwacken und stauenden Tonschiefern auf.

Das Klima wird gekennzeichnet durch Niederschläge, die im langjährigen Mittel nahe bei 1150 mm je Jahr liegen und auch in Extremfällen nicht stark davon abweichen. Der in unserem Beobachtungszeitraum 1951 bis heute gemessene niedrigste Jahresniederschlag betrug 1096 mm (1953), der höchste 1367 mm (1957). Die Verteilung der Niederschläge über das Jahr kann der nachstehenden Aufstellung über die Messungsergebnisse der meteorologischen Stationen Hilchenbach und Lahnhof für den Zeitraum 1891—1930 entnommen werden. Hilchenbach liegt auf 355 m Seehöhe in einem Tal am Westrand des nördlichen Teils des Untersuchungsgebietes, der Lahnhof dagegen auf 607 m Höhe im Zentrum des südlichen Drittels auf einem Plateau unweit der höchsten Erhebung des Gebietes.

Periode	Hilchenbach	Lahnhof
November	95 mm	90 mm
Dezember	124 mm	123 mm
Januar	114 mm	103 mm
Februar	91 mm	88 mm
März	84 mm	84 mm
April	81 mm	75 mm
Winter	589 mm	563 mm
Mai	70 mm	73 mm
Juni	87 mm	90 mm
Juli	110 mm	114 mm
August	98 mm	100 mm
September	87 mm	82 mm
Oktober	98 mm	101 mm
Sommer	550 mm	560 mm
Jahr	1139 mm	1123 mm

Die Niederschläge sind über die beiden Halbjahre ziemlich gleichmäßig verteilt mit einem gewissen Übergewicht in der jeweiligen Periodenmitte. In der gleichen Summe sind Sommer und Winter im 40jährigen Mittel praktisch gleich. In unserem Beobachtungszeitraum überwiegen allerdings seit dem Jahre 1953 die Sommerniederschläge infolge häufig auftretenden Sommermonsuns zum Teil sogar sehr stark, wie nachstehende Aufstellung für die Station *Lahnhof* zeigt:

W. W. Jahr	Winter mm	Sommer mm	Jahressumme mm
1953	478	626	1104
1954	345	833	1178
1955	564	690	1254
1956	427	694	1121
1957	660	707	1367
1958	576	785	1361
1953—1958	508	723	1231

In dem Extremjahr 1954 betrug der Juliniederschlag 231 mm und liegt damit nahe dem höchsten bisher gemessenen Monatsergebnis, während der November 1953 mit nur 16 mm den Niedrigstwert des gesamten Zeitraums von 1951 bis heute brachte.

Die Temperaturen zeigen eine verhältnismäßig geringe Amplitude und bewegen sich zwischen dem kältesten und wärmsten Monat im Bereich von etwa 16°. In den Plateaulagen liegt das Januarmittel bei —1,5° und das Julimittel bei +14,5°. Die mittlere Zahl der Frosttage beträgt 125, der Eistage 40. Besonders auffällig ist die hohe Zahl der Nebeltage; sie lag z. B. in den Jahren 1954—58 zwischen 100 und 120. Insgesamt gesehen ist das Klima als montan mit deutlich ozeanischem Charakter zu kennzeichnen.

Dem Vegetationscharakter nach gehört fast das gesamte Untersuchungsgebiet ursprünglich in den Bereich der Luzula-Buchenwälder und der Festuga-Buchenwälder, in denen die Buche eindeutig vorherrschte, der zum Teil Bergahorn und etwas Traubeneiche beigemischt war. An den Bächen und in Quellmulden kam auch der Bacherlen-Eschenwald vor, in den stark vernäßten Mulden fanden sich Birkenbrücher mit Moorbirke und Schwarzerle. Durch die Wirtschaft des Menschen wurden die begleitenden Holzarten der Buche größtenteils verdrängt, so daß vorwiegend reine Buchenbestände übrigblieben. Ebenso wie im übrigen Sauerland wurden auch im Staatsforst etwa von der Mitte des vorigen Jahrhunderts an in steigendem Maße Buchenbestände in reine Fichtenforsten umgewandelt, so daß im Laufe der Zeit der Anteil der Fichtenbestände an der Gesamtbestockung in Hilchenbach auf annähernd 50 % gestiegen ist. Die Umwandlung beginnt zumeist in den hohen Lagen und schreitet allmählich hangabwärts fort.

3. Die untersuchten Bestände

Die zu beobachtenden Bestände wurden in möglichst gleichmäßiger Verteilung über das gesamte Revier Hilchenbach ausgesucht. Es handelte sich dabei in der Regel um Flächenpaare von je einem auf gleichem Standort unmittelbar nebeneinander stockenden Buchen- und Fichtenreinbestand, wobei die Anforderung gestellt war, daß die beiden Bestände ungefähr der gleichen Altersstufe angehören und auch in höherem Alter möglichst gleichmäßig und voll, mindestens in der näheren Umgebung der Meßstellen bestockt sein sollten; eine Forderung, die ausnahmslos erfüllt werden konnte.

Insgesamt wurden 26 Buchen- und 30 Fichten-, zusammen also 56 Bestände, in Beobachtung genommen; ihre Verteilung nach Hangneigung, Hangrichtung und Bestandesalter ist folgende:

a) Hangneigung	eben	5—10°	11—20°	21—30°	31—45°	Sa.
Buche	3	1	10	9	3	26
Fichte	5	1	11	10	3	30

b) Hangrichtung	eben	N	W	S	O	Sa.
Buche	3	7	6	6	4	26
Fichte	5	7	6	8	4	30

c) Alter/Jahre	20—30	31—40	41—60	61—100	101—140	Sa.
Buche	2	3	1	12	8	26
Fichte	5	2	5	15	3	30

Die Aufstellung über die Hangneigung zeigt, daß die meisten Bestände an lehn bis steil geneigten Hängen liegen. Hinsichtlich der Hangrichtung ist die Verteilung ziemlich gleichmäßig, lediglich die Osthänge sind benachteiligt, da sie in dem Revier weniger häufig sind. Die Übersicht der Bestandesalter zeigt eine deutliche Bevorzugung der mittleren und älteren Baumhölzer.

4. Die durchgeführten Beobachtungen

a) *Die meteorologischen Messungen*

Zur Messung der Temperaturen und der Luftfeuchtigkeit wurde am Lahnhof eine meteorologische Station mit einem Wetterhäuschen für die Thermometer, einem Regenschreiber und 2 Hellmannschen Regenmessern eingerichtet. Die Temperaturen werden dreimal täglich abgelesen; der Regenschreiber läuft das ganze Jahr, da er im Winter durch eine elektrische Zuleitung beheizt werden kann.

Ein besonderes Problem war die Aufstellung der weiteren Regenmesser, die über das ganze Beobachtungsgebiet verteilt den Niederschlag auf dem Freiland im Vergleich zum Niederschlag im Waldbestand erfassen sollten. Es ist in einem großen, zusammenhängenden Waldgebiet oft nicht ganz einfach, genügend große Lücken zu finden, in denen Randeinflüsse der in der Umgebung liegenden Bestände nicht zu befürchten sind, und die außerdem für den Niederschlag des Gebietes, in dem die Beobachtungsstellen in den Beständen liegen, als repräsentativ angesehen werden können. Es gelang, 10 solcher Stellen zu finden, teils auf größeren Kahlflächen und Jungkulturen, teils auf Waldwiesen, die zu den beobachteten Beständen in günstiger Position liegen. Hier wurde je ein Hellmannscher Regenmesser aufgestellt und täglich abgelesen. Jedem der Freilandregenmesser wurde eine Gruppe von beobachteten Beständen zugeordnet.

Dem Charakter des Gesamtgebietes entsprechend, bewegten sich die Unterschiede im Niederschlag der Freilandstationen in verhältnismäßig engen Grenzen.

Nachstehend ist z. B. das Mittel des Jahresniederschlags der beiden W. W. Jahre 1952 und 1953 für die einzelnen Stationen angegeben:

Nr. 1 — 1100 mm	Nr. 6 — 1177 mm
Nr. 2 — 1114 mm	Nr. 7 — 1216 mm
Nr. 3 — 1186 mm	Nr. 8 — 1202 mm
Nr. 4 — 1150 mm	Nr. 9 — 1251 mm
Nr. 5 — 1165 mm	Nr. 10 — 1208 mm.

Die Stationen 1—4 befinden sich auf dem Plateau des Gebirgsrumpfs mit einer Neigung zum Lee, die Stationen 5—10 liegen auf der Luvseite. Die Station mit dem höchsten Niederschlag (Nr. 9 mit 1251 mm) liegt auf einem lehn geneigten, der Hauptwindrichtung WSW genau zugekehrten ausgedehnten Hang; die Station Nr. 1 dagegen mit dem geringsten Niederschlag auf sehr ausgeglichener Plateaulage in leichtem Windschatten.

b) *Die Messung des durch die Kronen tropfenden Niederschlags*

Hierzu wurden in der Regel in jedem der 56 Bestände an einer möglichst gleichmäßig bestockten Stelle je 2 Hellmannsche Regenmesser (200 cm² Öffnung) aufgestellt, die am Morgen nach jedem Tag mit Niederschlag abgelesen

wurden. Die Messungen wurden während der 5 Wasserwirtschaftsjahre 1951 bis 1955 (d. h. vom 1. Nov. 1950 bis 31. Okt. 1955) durchgeführt und dann abgeschlossen, da keine neuen Ergebnisse mehr zu erwarten waren. Lediglich in einem Flächenpaar, das in einem unmittelbar nebeneinanderliegenden älteren Fichten- und Buchenbaumholz (Abt. 106) an beobachtungsmäßig besonders günstiger Stelle liegt, wurde die Messung bis heute weitergeführt. Sie wurde hier durch Aufstellung von je 5 Regenmessern und je einer Meßwanne (500×20 cm Öffnung), die von *Delfs* aus den Harzer Versuchen übernommen wurden, verfeinert.

c) *Die Messung des Stammabflusses*

Nachdem zahlreiche Beobachtungen ergeben hatten, daß am Stamm der Buche ein merklicher Teil des Niederschlags unmittelbar abläuft und so auf den Boden gelangt, während diese Erscheinung bei der Fichte nur eine geringfügige Rolle spielt, war eine genaue Messung des Stammabflusses unerläßlich geworden. Es schien vor allem notwendig, diese Messungen nicht auf einzelne Bäume zu beschränken, wie dies bei den meisten bisher durchgeführten Untersuchungen die Regel war, sondern auf einen nicht zu kleinen Teil eines geschlossenen Bestandes auszudehnen, um eine einwandfreie Bezugsgröße für die Umrechnung der von allen Stämmen insgesamt abgeflossenen Litermenge auf mm Niederschlagshöhe im Bestand zu gewinnen und Zufälligkeiten in der Auswirkung verschiedenartiger Kronenausbildung und Stammform nach Möglichkeit auszuschalten. Hierzu wurden im Jahre 1955 je eine Versuchsfläche in dem oben bereits erwähnten älteren Fichten- und Buchenbaumholz der Abt. 106 unweit vom Lahnhof eingerichtet. Die Form der Flächen, die Position der Stämme sowie die Kronenprojektionen sind in Abbildung 1 dargestellt.

Auf der Buchenfläche, die 580 m² groß ist und an einem mit 25° geneigten Südhang auf 600 m Höhe liegt, stehen 22 Buchen und 1 Ahorn. Die ertragskundlichen Daten der Fläche im Zeitpunkt der Anlage waren:

Alter 90 Jahre, Stammzahl je ha 400, Mittelhöhe 25 m, mittl. Durchmesser in 1,3 m Höhe 28 cm, Ertragsklasse II, vollbestockt.

Am gleichen Hang, ein wenig mehr nach Westen gedreht, liegt in nur 150 m Entfernung die Fichtenfläche, die 320 m² Ausdehnung hat. Hier stehen 28 Fichten, was einer Stammzahl je ha von 875 entspricht. Alter 65 Jahre, Mittelhöhe 24 m, mittl. Durchmesser 25 cm, Ertragsklasse II, vollbestockt.

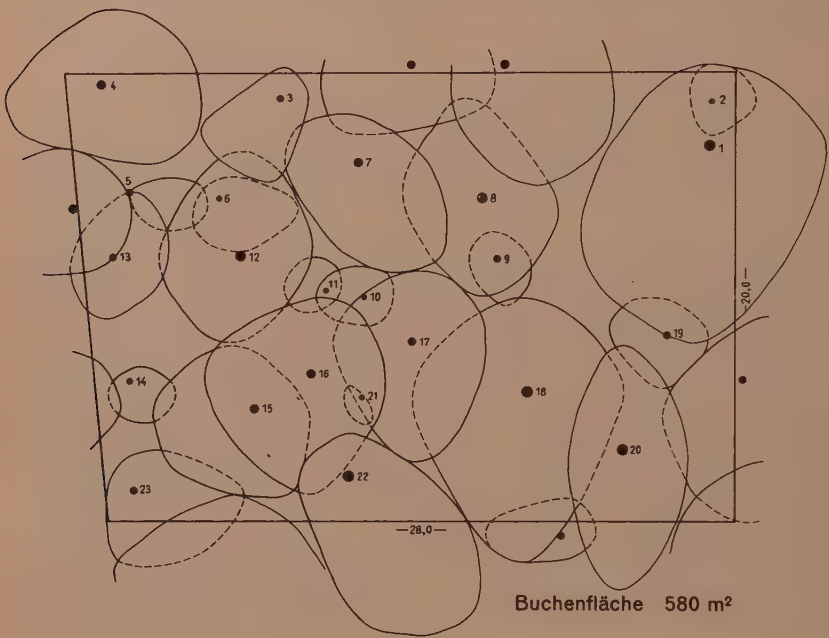
Die Kronenprojektionen des Buchenbestandes in Abt. 1 lassen erkennen, daß in einem vollgeschlossenen Bestand, zumal am steilen Hang, die Kronen sich zwar vielfach überdecken (durch gestrichelte Linien dargestellt), andererseits aber auch völlig freie Räume zwischen den Kronen offenlassen. Die Ausmessung der Kronenprojektionen hatte folgendes Ergebnis:

nicht überschirmte Kronenfläche	547 m²
überschirmte Kronenfläche	130 m².

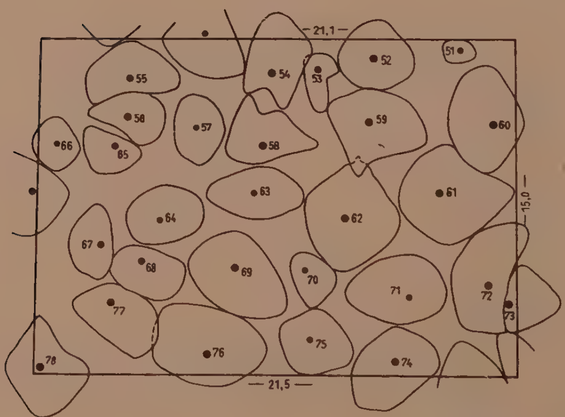
Zweifellos wäre es unzulässig gewesen, als Bezugsgröße für den Stammabfluß aller auf der Versuchsfläche stehenden Bäume nur deren freie, nicht unter Schirm liegende Kronenfläche (547 m²) zu wählen. Ebensowenig konnte aber die überschirmte Kronenfläche einfach dazugerechnet werden, wodurch man auf einen Betrag von 677 m² gekommen wäre, da die mehr oder weniger unter Schirm stehenden Bäume einen bedeutend geringeren Anteil des Niederschlags auffangen. Daher wurde die Fläche der Versuchs-

Abb. 1

Stammabflußflächen Hilchenbach Abt. 106



Buchenfläche 580 m²



Fichtenfläche 320 m²

fläche selbst — 580 m² — als die jeden Zweifel ausschaltende Bezugsgröße gewählt.

Die Kronenprojektionen der Fichtenfläche zeigen einen ganz anderen Charakter. Überschirmungen kommen praktisch überhaupt nicht vor. Die Gesamtfläche der Kronen beträgt nur 224 m², was einem Deckungsgrad (Schlußgrad) von 0,7 entspricht, obwohl die Stammgrundfläche in 1,3 m Höhe mit 41,7 m²/ha gegenüber einem Soll von 40,2 m² nach Wiedemann II, mäßige Durchforstung, den Bestand als gut vollbestockt ausweist. Ausschlaggebend für diese interessante Divergenz ist hier die Spitzkronigkeit der Fichte und vor allem die starke Windbewegung an dem der Hauptwindrichtung zugekehrten Hang, welche die Kronen gegenseitig abschleift. Als Bezugsgröße diente auch hier die aus den Abmessungen der Versuchsfläche sich ergebende Quadratmeterzahl (320 m²).

Zur Messung des Stammablaufs dienen Auffangrinnen aus Gummi, die eigens zu diesem Zweck gegossen wurden. Die Rinnen sind tief genug, daß selbst der stärkste Abfluß bei Starkregen sie nicht zum Überlaufen bringt. Sie sind etwa in Brusthöhe so um den Stamm gelegt, daß sie mit ausreichendem Gefälle seitlich in einen nach oben geschlossenen Auffangtrichter münden. An den Trichter ist ein Rohr angeschlossen, das in ein als Vorratsgefäß dienendes Faß führt, dessen Wasserstand an einem geeichten Steigrohr aus Glas abgelesen werden kann. Die Ablesung und Leerung der Fässer erfolgt nach jedem Regen am darauffolgenden Vormittag. Bei der Buche war es notwendig, für die stärkeren Stämme Fässer von 300 l Fassungsvermögen zu nehmen, und selbst diese Gefäße sind bei vereinzelten Starkregen übergelaufen. Bei Frost wurden die Messungen eingestellt.

Man könnte gegen diese Apparatur den Einwand erheben, daß in die oben offenen Auffangrinnen auch der durch die Kronen tropfende Niederschlag unmittelbar gelangen und dadurch das Messungsergebnis unzulässig erhöhen könnte. Dazu ist folgendes zu sagen: Die Rinne ist oben 4 cm breit, die Buchen hatten im Mittel einen Stammumfang von 90 cm, die Rinne bietet daher eine Auffangfläche von 360 cm². Diese Fläche ist aber nicht voll wirksam, da unmittelbar am Stamm durch den Schutz der Starkäste der Niederschlag erheblich herabgesetzt ist, und da außerdem infolge der Windwirkung immer nur eine Seite des Stammes unmittelbar getroffen wird. Die wirksame Auffangfläche dürfte daher kaum mehr als 150 cm² betragen. Im Sommer 1957 fielen im Buchenbestand 448 mm Niederschlag, das sind auf 150 cm² rd. 7 Liter. Am Stamm einer Buche sind aber im Durchschnitt in dieser Zeit 2915 Liter abgeflossen.

Die Messungen in der Fichtenfläche wurden nur in der frostfreien Zeit des Jahres 1956 durchgeführt und dann eingestellt, da das Ergebnis die von *Delfs* [1]) aus dem Harz berichteten Stammabflußzahlen im wesentlichen bestätigte. Die Messungen in der Buchenfläche laufen seit 1956 bis heute.

5. Die Ergebnisse

a) *Der durch die Kronen tropfende Niederschlag*

Die Fichtenkrone und die Buchenkrone bieten für das Durchdringen des Niederschlags bis zum Boden in ihrer Struktur völlig verschiedenartige Hindernisse. Die eng beieinanderstehenden Nadeln der Fichte bilden ein feines

[1]) Delfs u. andere: Der Einfluß des Waldes und des Kahlschlages auf den Abflußvorgang, den Wasserhaushalt und den Bodenabtrag. Mitt. d. Niedersächs. Landesforstverw. Heft 3, Hannover 1958.

Gitterwerk mit einer sehr großen Oberfläche und mit zahllosen Grenzflächen, zwischen denen sich leicht ein Wasserfilm von Nadel zu Nadel spannt, der durch die Adhäsion festgehalten wird. Die Blätter der Buche dagegen hängen einzeln und ohne eine andere als zufällige Berührung; sie besitzen eine glatte, geneigte Oberfläche, auf der das Wasser ohne lange zu haften, nach der Spitze zusammenfließt und in großen Tropfen abfällt. Außerdem steht die Buche im Winter (November bis April) kahl und bietet nur noch mit ihren nackten, glatten Ästen ein Hindernis für den Niederschlag. Es ist daher zu erwarten, daß die Menge des durch die Kronen tropfenden Niederschlags bei Buche und Fichte im Verhältnis zum Freilandniederschlag nicht nur saisonmäßig, sondern auch je nach der Klimalage sehr unterschiedlich ist.

In der Tabelle 1 sind die Monatssummen sowie die Summen der Halbjahre und Jahre 1951 bis 1955 als Mittelwerte der Ergebnisse in den 30 Fichten- und 26 Buchenbeständen zusammengestellt. Überprüft man zunächst die Monatswerte im *Winter*, so fällt sofort auf, daß bei der kahlstehenden Buche keineswegs der ganze Niederschlag auf den Boden gelangt, sondern daß immer noch ein recht erheblicher Anteil von dem Geäst und den Stämmen zurückgehalten wird. Geradezu überraschend ist aber die Tatsache, daß in nicht weniger als 11 von den 30 Wintermonaten in den Fichtenbeständen mehr Wasser in den Regenmessern ankam als in den Buchenbeständen. Zum Teil wird diese Erscheinung durch Schnee verursacht, der oft längere Zeit in den Fichtenkronen hängenbleibt und erst später bei Tauwetter oder starkem Wind herunterfällt. Während es sich aber hier meist nur um eine zeitliche Verschiebung handelt, hat sich der *Nebelniederschlag* als echter, dauernder Gewinn der Fichte gegenüber der Buche herausgestellt, da die Fichtenkrone vor allem im Winter aus den im Sauerland häufig tief hängenden ziehenden Wolken weit mehr Feuchtigkeit herausfiltert als das Geäst der Buche. Über die Einzelheiten wird in dem Abschnitt über die Interception noch berichtet. Jedenfalls ist es in erster Linie dem Nebelniederschlag zuzuschreiben, wenn im Durchschnitt des ganzen Beobachtungszeitraums in den Fichtenbeständen ebensoviel Niederschlag durch die Kronen getropft ist wie in den Buchenbeständen. Die Winterbilanz 1951—1955 ist folgende:

Niederschlag = 587 mm,

durch die Kronen getropft in den

Fichtenbeständen = 465 mm
Buchenbeständen = 465 mm.

Im *Sommer* ist die belaubte Buche der Fichte eindeutig überlegen. Von den 30 Sommermonaten der beobachteten 5 Jahre ist in 26 Monaten in den Buchenbeständen mehr Niederschlag durch die Kronen getropft als in den Fichtenbeständen, in 2 Monaten standen Buche und Fichte gleich, und nur in 2 Monaten (September 1952 und August 1953) war das Ergebnis bei der Fichte je um 1 mm höher. Das Mittel der 5 Jahre sieht folgendermaßen aus:

Niederschlag = 629 mm
durch die Kronen getropft in den Fichtenbeständen = 428 mm
in den Buchenbeständen = 457 mm.

Der Unterschied Buche-Fichte beträgt rd. 30 mm, das sind knapp 5 % des Sommerniederschlags. Angesichts der günstigen Architektur der Buchenkrone

TABELLE 1

Niederschlag und Menge des durch die Kronen getropften Wassers in 30 Fichten- und 26 Buchenbeständen

Periode	1951			1952			1953			1954			1955		
	Nieder-schlag	Durch d. Kronen getropft		Nieder-schlag	Durch d. Kronen getropft		Nieder-schlag	Durch d. Kronen getropft		Nieder-schlag	Durch d. Kronen getropft		Nieder-schlag	Durch d. Kronen getropft	
		Fi	Bu		Fi	Bu		Fi	Bu		Fi	Bu		Fi	Bu
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
November	209	165	160	193	158	144	179	156	139	18	10	12	96	68	75
Dezember	101	68	85	82	59	61	131	121	115	49	35	39	170	129	133
Januar	138	132	112	194	172	160	41	49	37	110	107	92	97	68	75
Februar	91	62	74	100	110	90	92	87	76	66	48	56	115	83	91
März	121	88	95	104	81	80	21	12	16	47	35	37	81	49	58
April	90	57	68	24	10	17	53	29	38	63	43	48	59	35	44
Winter	750	572	594	697	590	552	517	454	421	353	278	284	618	432	476
Mai	75	51	56	41	25	29	81	57	59	77	57	59	130	71	92
Juni	81	54	59	109	73	76	116	82	86	86	61	66	104	73	73
Juli	50	31	37	54	35	40	153	105	115	234	173	174	94	54	63
August	139	102	104	97	67	69	127	96	95	135	95	104	156	89	106
September	85	63	65	162	119	118	49	26	33	176	129	136	121	70	75
Oktober	25	19	20	144	103	105	53	42	42	122	88	95	68	30	33
Sommer	455	320	341	607	422	437	579	408	430	830	603	634	673	387	442
Jahr	1205	892	935	1304	1012	989	1096	862	851	1183	881	918	1291	819	918

hätte man eine noch größere Überlegenheit der Buche erwarten können. Doch hat sich auch hier der Nebelniederschlag als ein bedeutender Faktor zugunsten der Fichte herausgestellt, da auch im Sommer Nebelbildungen durch tief hängende Wolken häufig vorkommen.

b) *Der Stammabfluß*

Den Stammabfluß der *Fichte* in der frostfreien Zeit des Jahres 1956 zeigt Tabelle 2. Im Durchschnitt des Sommers sind *0,7 %* des Niederschlags am Stamm abgeflossen. Im November und Dezember wurde dieser Wert zwar noch unterschritten, es kann aber doch angenommen werden, daß das Abflußprozent im Winter, zumal bei häufigen Nebeltagen, etwas höher liegt und vielleicht 1,0 % erreicht. *Jedenfalls ist der Stammabfluß bei der Fichte von so geringer Bedeutung, daß er im Wasserhaushalt des Bestandes praktisch keine Rolle spielt.* Der Stammabfluß der *Buche* in den Jahren 1956 bis 1958 ist in Tabelle 3 wiedergegeben. Bei der Buche mit ihrer glatten Rinde und ihren meist nach oben gereckten Ästen spielt der Stammabfluß offenbar eine sehr große Rolle. Im Sommer betrug er im Mittel der drei Jahre *16,6 %* des Niederschlags. Trotz ziemlicher Unterschiede der Monatsmittel bewegen sich die Mittel der drei Sommer in erstaunlich engen Grenzen, was auf eine ziemliche Ähnlichkeit des Klimas gerade dieser drei Jahre zurückzuführen ist.

TABELLE 2

Stammabfluß der Fichte im Jahre 1956

Periode	Niederschlag mm	Stammabfluß		
		Liter	mm	%
Mai				
Juni	57,6	0	0,0	0,0
Juli	163,6	293	0,9	0,5
August	121,5	238	0,7	0,6
September	80,4	302	0,9	1,1
Oktober	106,1	296	0,9	0,9
November	119,0	194	0,6	0,5
Dezember	86,8	148	0,5	0,6
Sommer	529,2	1129	3,5	0,7

Im Winter waren die Messungen auf die frostfreie Zeit beschränkt, daher liegen Ergebnisse nur von insgesamt 7 Monaten vor, in denen im Durchschnitt *20,4 %* des Niederschlags am Stamm abgeflossen sind.

Unterstellt man, daß bei der Fichte in den drei Sommern 0,7 % und in den drei Wintern 1,0 % des Niederschlags am Stamm abgelaufen sind, und daß bei der Buche der Durchschnitt von 20,4 % für die ganze Wintersaison

TABELLE 3

Stammabfluß der Buche in den Jahren 1956—58

Periode	1956				1957				1958			
	Niederschlag	Stammabfluß			Niederschlag	Stammabfluß			Niederschlag	Stammabfluß		
		Liter	mm	%		Liter	mm	%		Liter	mm	%
März					95,8	18 780	32,3	33,7				
April					43,3	4 201	7,2	16,6	70,8	7 709	13,3	18,8
Mai					60,8	3 209	5,5	9,0	164,2	16 625	28,7	17,5
Juni	57,6	5 742	9,9	17,2	50,2	3 274	5,6	11,2	129,2	11 422	19,7	15,3
Juli	163,6	12 296	21,2	12,9	135,3	12 454	21,5	15,9	105,8	8 449	14,6	13,8
August	121,5	12 129	20,9	17,2	148,0	14 995	25,9	17,5	172,3	15 497	26,7	15,5
September	80,4	9 571	16,5	20,5	257,8	25 825	44,5	17,2	86,4	9 396	16,2	18,8
Oktober	106,1	12 110	20,9	19,7	55,1	7 278	12,5	22,7	127,1	14 709	25,4	20,0
November	119,0	11 328	19,5	16,4	53,3	6 740	11,6	21,8	42,2	4 345	7,5	17,8
Dezember	86,8	7 539	13,0	14,9								
Sommer	529,2	51 848	89,4	16,9	707,2	67 035	115,5	16,3	785,0	76 098	131,3	16,7

zutrifft, so erhält man folgende Abflußzahlen in mm für die Jahre 1956 bis 1958:

	Buche			Fichte		
	1956	1957	1958	1956	1957	1958
Winter	85	132	115	4	7	6
Sommer	115	116	131	5	5	6
Jahr	200	248	246	9	12	12

Allein durch den Stammabfluß sind jährlich in dem Buchenbestand rd. 200 bis 230 mm mehr Niederschlag auf den Boden gelangt als in dem Fichtenbestand.

Der Stammabfluß jedes einzelnen Baumes der Buchenfläche wurde in seiner Abhängigkeit von der Kronenquerschnittsfläche, dem Kronenvolumen und dem Stammumfang in Brusthöhe untersucht. Es zeigte sich, daß der *Stammumfang in 1,3 m Höhe* bei weitem die beste Korrelation zum Abfluß hat, nicht zuletzt natürlich deshalb, weil er am genauesten gemessen werden kann. In Abbildung 2 ist diese Abhängigkeit durch die Abflußsumme jedes Baumes für die Zeit vom April bis November 1958 dargestellt. Nach der oben geschilderten Größenordnung des Abflusses wird es nicht mehr wundern, daß an den stärksten Bäumen in diesem Zeitraum *über 9000 Liter Wasser* abgelaufen sind. Die Durchschnittskurve der Einzelwerte ist nur im unteren Teil gestreckt, bei den starken Bäumen flacht sie sich ab, da bei diesen Bäumen sich die Krone in zunehmendem Maße kugelig abwölbt, so daß der Anteil der nach außen hängenden und dadurch das Wasser nicht mehr zum Stamm leitenden Äste zunimmt. Wie Vergleichsmessungen in einem jüngeren Baumholz zeigten, in dem alle Äste nach oben gestreckt sind, tritt diese Erscheinung dort nicht auf.

Alle Klimafaktoren, welche die Menge des durch die Kronen tropfenden Niederschlags beeinflussen, wirken in gleicher Weise auch auf den Stammabfluß. An erster Stelle steht hier die *Höhe des Niederschlags.* In der Tabelle 4 ist der Stammabfluß aller 23 Stämme der Buchenfläche in der Summe der drei Sommer 1956 bis 1958 der Höhe des Niederschlags gegenübergestellt. Hierbei konnte eine ziemlich weitgehende Aufschlüsselung nach Niederschlagsstufen erfolgen, da die lange Dauer der Untersuchungsperiode und die relativ große Anzahl der gemessenen Bäume eine für gute Mittelbildung genügend große Anzahl von Fällen auch für sehr enge Stufen lieferte und auch die durch andere Faktoren (Intensität der Regen, Luftfeuchtigkeit, Stärke des Windes usw.) verursachten Schwankungen weitgehend ausglich.

Die Spalte „Anzahl der Regentage“ zeigt, daß der Schwerpunkt bei Niederschlägen zwischen 5 und 10 mm liegt. Der Stammabfluß, der vom schwächsten bis zum starken Regen um mehr als den 300fachen Betrag (von 7 bis über 2300 Liter) steigt, beginnt bei den Stufen bis 2 mm mit sehr kleinen Mengen, die etwa 2—4 % des Niederschlags ausmachen. Immerhin ist aber bemerkenswert, daß selbst bei so geringen Niederschlägen bereits ein Stammabfluß in Gang kommt, was auf eine ungewöhnlich schwache

Abb. 2

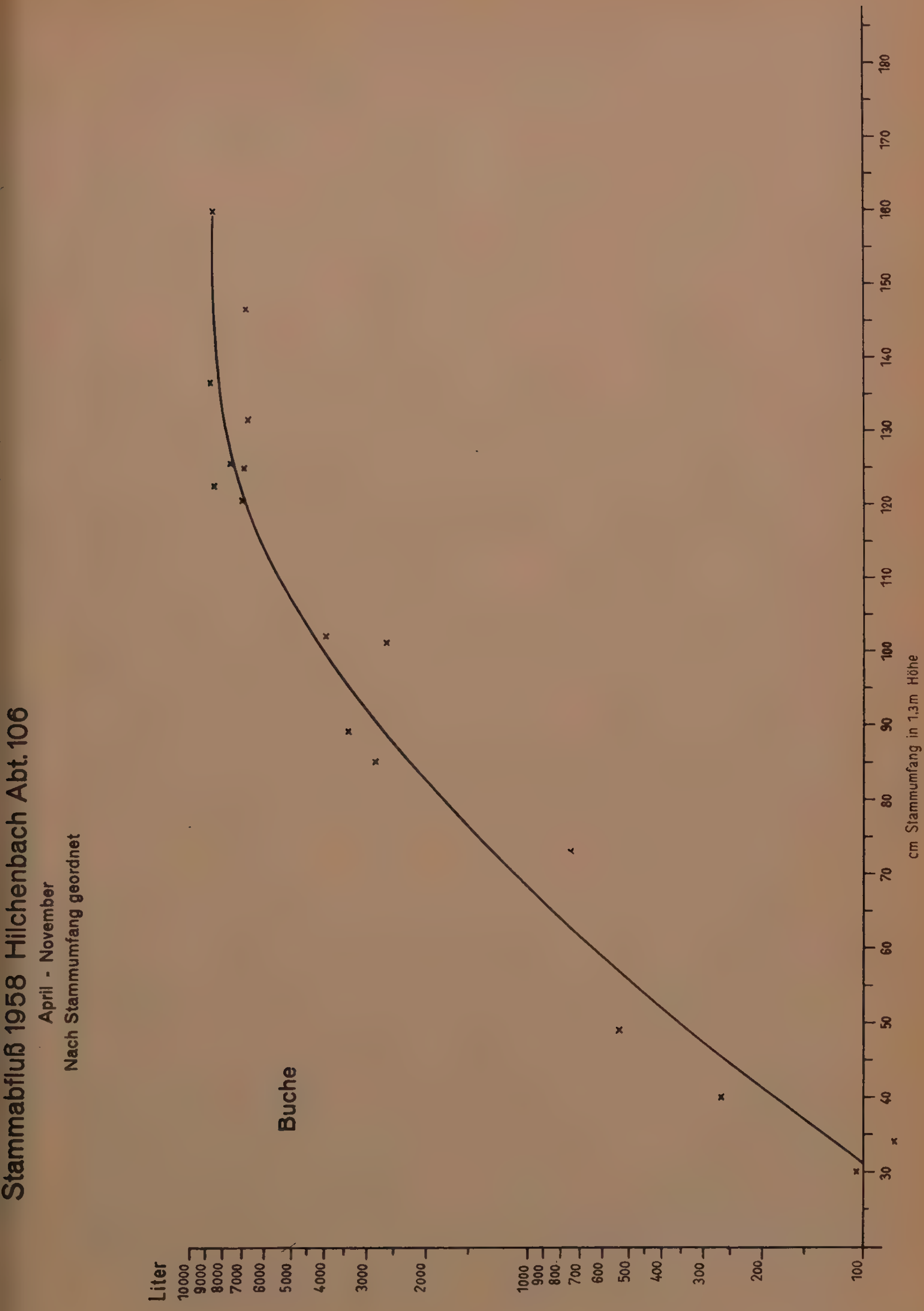

Stammabfluß 1958 Hilchenbach Abt. 106
April - November
Nach Stammumfang geordnet
Buche
Liter
10000 9000 8000 7000 6000 5000 4000 3000 2000 1000 900 800 700 600 500 400 300 200 100
30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
cm Stammumfang in 1,3m Höhe

TABELLE 4

Stammabfluß in Beziehung zur Höhe des Niederschlags in der Buchenfläche

Summe der 3 Sommer 1956—58

Niederschlags-stufe mm	Anzahl der Regen-tage	mittlerer Nieder-schlag je Regentag mm	Mittlerer Stammabfluß je Regentag		
			Liter	mm	% des Nieder-schlags
0 — 1,0	36	0,5	7	0,01	2,0
1,1— 2,0	44	1,5	32	0,06	4,0
2,1— 3,0	25	2,5	208	0,36	14,4
3,1— 5,0	38	4,0	310	0,53	13,3
5,1—10,0	71	7,5	733	1,27	16,9
10,1—15,0	34	12,5	1 207	2,08	16,6
15,1—20,0	21	17,5	1 879	3,24	18,5
über 20,0	22	26,0	2 329	4,02	15,5
Summe/Mittel	291	6,91	670	1,16	16,8

Speicherkapazität der Krone und einen sehr niedrigen Stammbenetzungswert bei der Buche deutet. *Bereits von der 2-mm-Grenze an steigt der Abfluß sehr rasch und erreicht bald den bei 16—17 % des Niederschlags liegenden Mittelwert, der auch in der höchsten Stufe keine nennenswerte Absenkung erfährt.*

Bei jedem Starkregen von über 20 mm sind an jedem Stamm im Durchschnitt 100 Liter abgelaufen. Da infolge der meist mehr oder weniger ausgeprägten Spannrückigkeit, vor allem der unteren Teile, des Buchenstammes der Großteil des Wassers in der tiefsten Rinne abfließt, ist die oft deutlich erkennbare erodierende Wirkung des Wassers am Stammfluß erklärlich.

c) *Die Interception*

Die Messungen des Stammabflusses haben gezeigt, daß bei der Buche eine Berechnung der Interception nur aus den Ergebnissen des Niederschlags im Bestand zu viel zu hohen Werten führt, da durch den Stammabfluß eine erhebliche zusätzliche Wassermenge auf den Boden gelangt. Eine ganz korrekte Untersuchung der Interception würde daher in jedem Bestand eine Anlage zur Messung des Stammabflusses erfordern. Es ist aber fraglich, ob sich der damit verbundene sehr hohe Aufwand lohnen würde, da die Interception nur ein, wenn auch sehr wichtiger Faktor im Wasserhaushalt eines Bestandes ist. Bei unseren Untersuchungen, welche sich hinsichtlich des Stammabflusses nur auf zwei repräsentative Bestände erstreckten, wurde mindestens hinsichtlich der Größenordnung des Unterschieds von Buchen- und Fichtenbeständen ein ausreichend zuverlässiges Ergebnis erzielt. Mit dem Vorbehalt, der jeder Extrapolation innewohnt, wurde daher für die Berechnung der *wahrscheinlichen Interception* der in den Jahren 1951 bis 1955 beobachteten 26 Buchen- und 30 Fichtenbestände unterstellt, daß der Stammabfluß im Sommer bei Buche 16,6 % und bei Fichte 0,7 % des Niederschlags

betragen hat. Für das Winterhalbjahr wurden die gleichen Sätze angenommen, obwohl sie bei Buche mit Sicherheit wesentlich, bei Fichte wahrscheinlich etwas höher sind. Das Ergebnis bringt Tabelle 5.

Die Interception betrug

im Winter	bei Fichte	20,1 %
	bei Buche	4,3 %
im Sommer	bei Fichte	31,2 %
	bei Buche	10,8 %

des Niederschlags.

In Millimeter des auf den Boden gelangten Wassers ausgedrückt, brachte die Buche gegenüber der Fichte einen Gewinn von

93 mm im Winter
128 mm im Sommer
221 mm im Jahr.

Der Jahresgewinn schwankte zwischen 163 mm (1953) und 303 mm (1955).

Unter den verschiedenen Faktoren, welche die Höhe der Interception beeinflussen, sei hier nur auf die beiden wichtigsten: Höhe des Niederschlags und Nebel eingegangen. Ein korrekter Vergleich von Fichte und Buche ist nur für die beiden Bestände möglich, in denen der Stammabfluß gemessen wurde, und auch hier nur in dem Zeitraum der tatsächlich durchgeführten Messungen.

Die *Interception nach Niederschlagsstufen* im Mittel der Sommer 1956 bis 1958 in dem Fichten- und Buchenbestand der Abt. 106 bringt nachstehende Übersicht:

Niederschlagsstufe mm	Fichte %	Buche %	Differenz
0 — 1,0	81,7	71,9	9,8
1,1— 2,0	63,2	55,2	8,0
2,1— 3,0	54,8	24,8	30,0
3,1— 5,0	46,9	18,4	28,5
5,1—10,0	32,8	16,5	16,3
10,1—15,0	30,3	16,2	14,1
15,1—20,0	25,5	17,2	8,3
über 20,0	24,1	17,7	6,4

Die letzte Spalte mit der Differenz Fichte-Buche beleuchtet aufs deutlichste die *grundverschiedene Interceptionsdynamik der beiden Baumarten.* Bei den Schwachregen bis 2 mm, bei denen der Stammabfluß der Buche noch nicht in Gang gekommen ist, und außerdem bei den Starkregen über 15 mm, die schließlich alle Unterschiede nivellieren, stehen sich Fichte und Buche relativ nahe. Der von 2 mm aufwärts schlagartig einsetzende Stammabfluß der Buche läßt den Unterschied auf einen Höchstwert anschwellen, der erst langsam und von der 5-mm-Stufe aufwärts rascher sinkt. Aus der Aufstellung geht hervor, daß *in einem Klimagebiet, dessen Sommerregen sich*

TABELLE 5

Die Interception von 26 Buchen- und 30 Fichtenbeständen im Staatsforstrevier Hilchenbach Wasserwirtschaftsjahre 1951—1955

W.W. Jahr	Periode	Niederschlag mm	Fichte					Buche				
			Auf den Boden gelangt			Interception		Auf den Boden gelangt			Interception	
			Durch die Kronen getropft	Am Stamm abgelaufen	Gesamtmenge	mm	v. H. des Niederschlags	Durch die Kronen getropft	Am Stamm abgelaufen	Gesamtmenge	mm	v. H. des Niederschlags
			mm	mm	mm	mm	%	mm	mm	mm	mm	%
1951	Winter	750	572	6	578	172	22,9	594	125	719	31	4,1
	Sommer	455	320	4	324	131	28,8	341	74	415	40	8,8
	Jahr	1 205	892	10	902	303	25,1	935	199	1 134	71	5,8
1952	Winter	697	590	5	595	102	14,6	552	116	668	29	4,2
	Sommer	607	422	4	426	181	29,8	437	101	538	69	11,4
	Jahr	1 304	1 012	9	1 021	283	21,7	989	217	1 206	98	7,5
1953	Winter	517	454	3	457	60	11,6	421	86	507	10	1,9
	Sommer	579	408	4	412	167	28,8	430	95	525	54	9,3
	Jahr	1 096	862	7	869	227	20,7	851	181	1 032	64	5,8
1954	Winter	353	278	1	279	74	21,0	284	58	342	11	3,1
	Sommer	830	603	7	610	220	26,5	634	137	771	59	7,1
	Jahr	1 183	881	8	889	294	24,9	918	195	1 113	70	5,9
1955	Winter	618	432	5	437	181	29,3	476	102	578	40	6,5
	Sommer	673	387	5	392	281	41,8	442	112	554	119	17,7
	Jahr	1 291	819	10	829	462	35,8	918	214	1 132	159	12,3
Mittel	Winter	587	465	4	469	118	20,1	465	97	562	25	4,3
1951—	Sommer	629	428	5	433	196	31,2	457	104	561	68	10,8
1955	Jahr	1 216	893	9	902	314	25,8	922	301	1 133	93	7,6

vorwiegend in der Stufe von 2—5 mm bewegen, der Unterschied zwischen Buche und Fichte am höchsten sein wird.

Eine besondere Beachtung verdient unter den Verhältnissen in Hilchenbach der *Einfluß des Nebels.* In den drei Jahren 1956 bis 1958 wurden an der Station Lahnhof folgende Nebeltage festgestellt:

	Winter	Sommer	Jahr
1956	38	66	104
1957	55	61	116
1958	40	69	109

Der Nebel kommt sehr häufig — vor allem im Sommer — durch das Eintauchen des Gebirges in den unteren Wolkensaum zustande. Der Nebel unterdrückt die Verdunstung, benetzt Krone und Stamm und begünstigt — vor allem bei der Buche — den Stammabfluß.

Im Mittel der drei Sommer 1956 bis 1958 betrug in der Abt. 106 die Interception

	Fichte	Buche
in den Tagen mit Nebel	27,4 %	16,0 %
in den Tagen ohne Nebel	39,9 %	26,4 %.

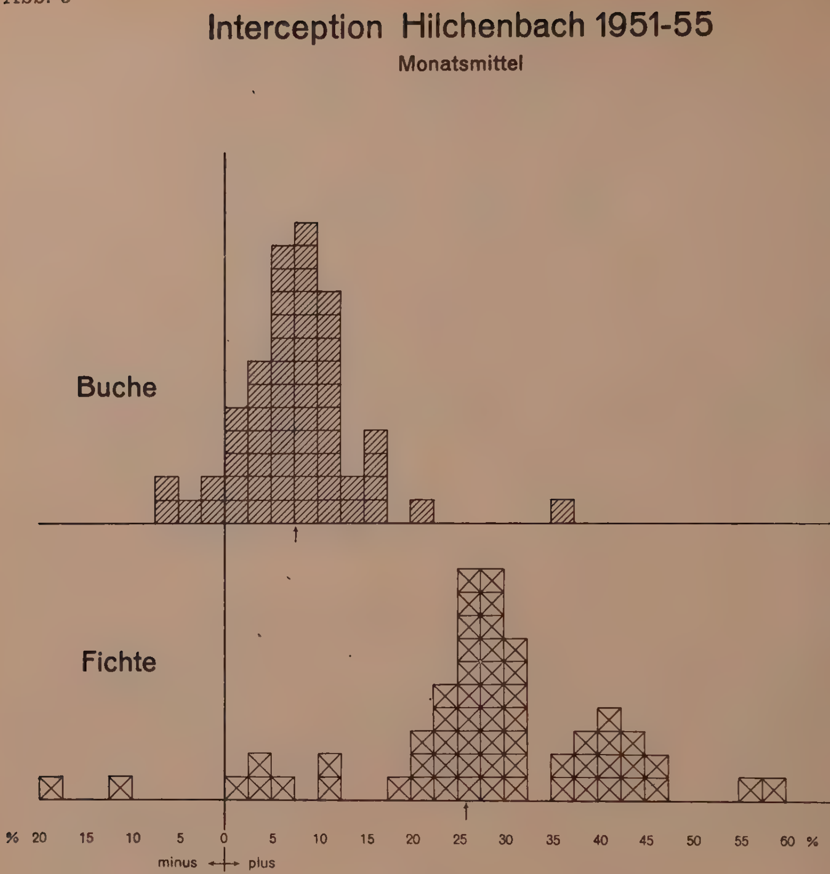
Besonders aufschlußreich ist die Beobachtung von typischen Einzeltagen. Am 16. März 1957 strichen fast den ganzen Tag über stark ziehende Nebelschwaden durch den Wald. Bei Temperaturen zwischen + 6 und 7° betrug der Niederschlag an der Wetterstation Lahnhof *6,4 mm.* In dem Buchen- und Fichtenbestand wurden folgende Werte gemessen:

Abt. 106	Durch die Kronen getropft mm	Am Stamm abgelaufen mm	Summe mm	Überschuß gegenüber dem Niederschlag mm
Fichte	14,7	—	14,7	8,3
Buche	6,7	4,7	11,4	5,0

Die Fichtenkronen haben mehr als den doppelten Betrag an Nebelniederschlag eingebracht, als im Freiland auf den Boden kam. Die kahl stehenden Buchenkronen dagegen brachten an direkt abtropfendem Wasser nur einen kleinen Zuschlag (0,3 mm) zu dem Freilandniederschlag. Dafür lief aber das Nebelkondenswasser in ganzen Strömen an den Stämmen herunter, so daß auch in dem Buchenbestand 5 mm Gewinn gegenüber dem Freiland eintrat.

Ein Beispiel im Sommer ist der 21. August des gleichen Jahres. Temperaturen + 11—13°, starke Wolkenschwaden nach Tagen stärkster Bewölkung

Abb. 3



und z. T. sehr hoher Niederschläge. Niederschlag der Freilandstation 9,4 *mm*. Ergebnisse im Bestand:

Abt. 106	Durch die Kronen getropft mm	Am Stamm abgelaufen mm	Summe mm	Überschuß gegenüber dem Niederschlag mm
Fichte	15,2	—	15,2	5,8
Buche	10,7	3,4	14,1	4,7

Diese Beispiele sind zwar besonders prägnante Fälle; es muß aber festgehalten werden, daß es nur dem ungewöhnlich hohen Nebelniederschlag zuzuschreiben ist, wenn in mehreren Wintern nicht nur an einzelnen Tagen,

sondern im ganzen Monatsmittel der 30 Fichten- bzw. 26 Buchenbestände die Interception negativ war oder sehr nahe bei Null stand.

Zum Abschluß der Untersuchung über die Interception sind in der Abbildung 3 die Monatsmittel als Mittelwert der 30 Fichten- bzw. 26 Buchenbestände für die 60 Monate 1951—1955 dargestellt. Jedes Kästchen der Zeichnung bedeutet einen Monat. Der Pfeil unter der Abszisse gibt die Lage des arithmetischen Mittels an. Das Bild zeigt noch einmal klar den Unterschied von Buche und Fichte, der sich in folgenden Zahlen zusammenfassen läßt:

	Fichte	Buche
Mittlere Interception der 5 Jahre	25,8 %	7,6 %
Höchstes Monatsmittel	58,3 %	35,3 %
Niedrigstes Monatsmittel	— 19,5 %	— 7,3 %
Amplitude der Monatsmittel	77,8	42,6

Besonders typisch ist bei der Fichte die hohe, bei der Buche die viel geringere Schwankung um den Mittelwert. Im Bereich von ± 5 % des Mittelwertes der 5 Jahre lagen

bei der Fichte 29 Monatsmittel,
bei der Buche 42 Monatsmittel.

Daraus geht klar hervor, wie außerordentlich verschieden hinsichtlich der Interception ein Fichtenbestand je nach der herrschenden Klimalage bewertet werden muß. Die Buche zeigte viel engere Reaktionsnormen und brachte insgesamt einen *bedeutenden Gewinn an nutzbarem Wasser gegenüber der Fichte.*

Es darf aber nicht übersehen werden, daß in anderen Klimalagen sich das Verhältnis verschieben kann, wobei die Fichte wahrscheinlich flexibler ist als die Buche. Nimmt man noch hinzu, daß bei der Gestaltung des gesamten Wasserhaushaltes die Evaporation des im Gegensatz zur Fichte im Winter kahl stehenden Buchenwaldes vor allem in mehr kontinentalem Klima eine wesentliche Rolle spielen kann, so wird klar, welch große Vorsicht bei der Beurteilung der in Hilchenbach erzielten Ergebnisse vor allem hinsichtlich ihrer Übertragung auf andere Gebiete geboten ist.

FOREST WATERSHED RESEARCH AND METHODS USED IN THE UNITED STATES

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RÉSUMÉ

Le but des recherches concernant la gérance des zones boisées aux Etats Unis est d'obtenir les connaissances necessaires pour servir de base pour un programme de 1) réhabilitation de zones denudées causant des inondations et des sédimentations ; 2) protection du sol et des resources d'ean pendant que le terrain est utilisé, notamment pour la production et la recolte de bois, pâturage de bétail, habitation de bêtes sauvages, et récréation; 3) augmentation du rendement d'eau ou amélioration des périodes de son rendement.

Le programme de recherche comprend des études fondamentales et d'application. Dans les recherches fondamentales sont inclues des études des procédés hydrologiques et d'érosion, du caractère de la végétation, et des possibilités de les modifier. Les recherches d'application, basées sur les résultats des études fondamentales, comprennent les traitements des zones designées pour obtenir des buts spécifiés.

Les recherches des procédés fondamentaux sont faites dans des laboratoires sur des placettes permanentes, ou par prélèvement d'échantillons de populations choisies sur une base statistique correcte. Les études d'application s'étendent généralement sur un zone entière.

The concept of forest watershed management is comparatively new in the United States. As recently as the beginning of the present century foresters were concerned primarily with the protective aspects of forest as they related to runoff, erosion, sediment yields, and streamflow regimen. Foresters of that day were strongly influenced by their concern about the exploitation of forest lands that had been carried on for more than a century past. On the other hand, equally well intentioned people expressed considerable doubt as to the effects of forests on streamflow. Unfortunately, the differences of opinion were often guided to a major degree by emotion rather than a sound basis of facts.

Up until about 35 years ago, little research had been carried on in the United States concerning the influence of forests on runoff, erosion, local climate, and the like. Most of the information available at that time was based on studies in various European countries. Some of the information derived from these European studies was directly applicable, but it soon became increasingly evident that much additional study was needed due to the great variations in climate, soils, geology, and vegetative types found in the United States.

The pioneer watershed study in the United States was the famous Wagon Wheel Gap investigation. This study, carried on cooperatively by the U. S. Forest Service and Weather Bureau, was intended to determine the effect on runoff and erosion of cutting all the forest growth on a small calibrated watershed. The results of the study, reported in 1928, did little to settle the controversy concerning the hydrologic effects of forests. Superficially, the results could be used to lend some support to both sides of the argument. In my opinion, the main value of this study was that it showed there was no

clear-cut "black-or-white" answer to the question and that the very complicated relationships could only be determined through sound scientific research.

During the past 25 years the Forest Service of the U. S. Department of Agriculture, in cooperation with other Federal agencies, state agencies, universities, municipalities, and various industries, has developed a program of comprehensive research into the influences of forest and range vegetation upon runoff, erosion, sedimentation, and streamflow regimen, and the principles and methods of repairing and managing watersheds in such cover. The major objectives of this research effort are: (1) a sounder understanding of the interactions of vegetation types with their natural and cultural environments and their effect upon the operation of the water cycle, including erosional as well as hydrologic processes; (2) the development of more effective methods for stabilizing and improving waterflow on damaged forest and related rangelands; (3) methods of detecting incipient instability and of protecting, utilizing, and managing such lands to insure their proper hydrologic functioning, and to reduce the adverse effects of various forms and degrees of use upon soil and water values; and (4) techniques to increase or otherwise improve the usefulness of water supplies from such lands by alteration of the vegetation or by management of the snowpack in mountain watersheds.

These objectives are necessary to meet the needs of the modern professional foresters, who in a nationwide referendum in December 1947 approved a policy on multiple use. This policy reads as follows: (1)

Policy on Multiple Use

The Society of American Foresters subscribes to the principle of multiple use of forest and other wildlands, meaning by that a conscious effort to manage each unit of land for its highest sustained productivity. In some cases, this may mean utilization of an identical area for several purposes at the same time; in others, utilization of different parts of an administrative unit for different single or limited purposes. In all cases, the development of management policies and plans requires adequate recognition of all resources and benefits, with due consideration of the relative social and economic values of each resource present and of the effects of utilizing one resource upon the stability, value, and appreciation of the others. More specifically:

1. Satisfactory conditions of soil, cover, and waterflow are basic, and all forest lands, regardless of type or purpose of ownership, should be so managed and protected as to maintain fully those conditions;

2. Management policies, plans, and practices governing the use of a principal resource, such as timber, should take into account and make specific provisions for all the resources capable of use or appreciation, not just the principal resource alone;

3. Methods or intensities of practice, as in timber harvesting, livestock and big game grazing, recreation, and road and trail construction, which may bring about soil instability or adversely affect runoff and streamflow conditions, should be modified or avoided;

4. Knowledge and skill in multiple-use management are as yet inadequately developed. Research on different phases of wildland use should be more effectively coordinated on the same experimental areas, and the study of multiple-use problems should be made an integral part of such research;

(1) Journal of Forestry, V. 46, No. 1, pp. 15, Jan. 1948.

5. Foresters, as managers of wildlands, have a professional obligation to keep abreast of scientific findings on the characteristics and interrelations of forest resources, and of the effects of developing any one of them upon the others.

It is apparent that the carrying out of such a policy must lean heavily upon research findings to guide the increasing intensity of forest and range management.

Watershed management research is now being carried on in all major regions of the country, including Alaska and Hawaii. The program in each region is aimed at answering problems characteristic of that region and collectively to establish basic principles applicable to all.

The research program consists of both basic and applied types of studies. Included in the former are studies of: (1) hydrologic processes such as precipitation type and distribution, interception of precipitation by vegetation, infiltration, surface runoff, evapotranspiration, percolation, and streamflow characteristics; (2) erosional processes such as detachment and transport of soil particles, gully formation, landslides; (3) vegetation characteristics such as depth and pattern of root development, amount and time of water use by different species of plants, amount and type of litter formation; (4) soil biological activities including studies of the macro and micro soil organisms in developing various soil characteristics. Included also in these studies are determinations of the effect of various vegetative changes and land uses on these basic processes and characteristics.

Applied studies include: (1) development and evaluation of measures intended to rehabilitate damaged watersheds and reduce storm runoff and erosion, by increasing the vegetative cover and also such measures as contour furrowing or terracing, gully plugging, stream channel control and other supplementary structures; (2) evaluation of logging operations and methods of grazing so designed as to prevent excessive soil disturbance and compaction that results in accelerated runoff and erosion; and (3) evaluation of treatments intended to increase total water yield or the yield during specific seasons of the year.

Thus it may be seen that the research program is aimed at, first, obtaining a thorough understanding of the basic processes and characteristics involved and affecting water and sediment movement within and out of forest watersheds, and second, to develop and evaluate treatments intended to attain certain desired objectives of management.

The methods used for carrying on the various phases of the research program range from precise measurements carried out in laboratories to studies carried out on entire watershed units. Studies of processes may be carried out in the laboratory where certain variables may be artificially controlled, or they may be carried out under natural conditions by a system of sampling whereby variables may be controlled through statistical analysis, or they may be carried out on permanent small plots or lysimeters where variables may be controlled both artificially and by statistical procedures. Evaluation of treatments intended to attain certain objectives is usually carried out on large plots or small comparatively homogeneous watersheds. This constitutes the first step towards practical application of knowledge obtained from the basic studies of processes. The final step in the research procedure constitutes a transition from experimental research to application as a management procedure. This is the pilot testing of promising management practices on large watersheds. In this phase a management plan is de-

veloped for a large watershed and provision made for determining the effects of such practices on the timing, quantity, and quality of water yield and amount of sediment production, as well as measurements to determine the effect of these practices on other products and uses of the land such as for timber and forage production, recreation, and wildlife habitat.

A number of the papers following, both on this symposium as well as that on lysimeters, will illustrate more fully some of the various types of studies included in our research program, illustrate some of the methods used, and present some results. They include both basic studies of processes as well as applied studies.

In conclusion, I would like to emphasize that our research program is intended to furnish a sound basis of knowledge for the use of those responsible for the management of wildlands, whether publicly or privately owned. The land manager makes the administrative decisions as to how and for what purposes a piece of land will be used; we in research try to provide him with sound physical information to assist him in making decisions.

FORESTS AND FLOODS IN THE NORTHWESTERN UNITED STATES

by HENRY W. ANDERSON AND ROBERT L. HOBBA (*)

CONCLUSIONS

1. In northwestern United States clear cutting of forests and forest fires have increased floods from watersheds for both rain-snowmelt floods and snowmelt floods.
2. Where stocking of the forest has recovered with time in a watershed, the flood peak discharges have again decreased.
3. For watersheds with geology of marine sediments and for those with volcanic rocks the forest effects on floods were the same.
4. For great storms and small storms the effects of forest cutting on floods were the same.
5. For rain-snow floods, forest effects on floods were greatest in the zone below the snowmelt line in a given storm and watershed. Evaluation of the meteorological, topographic, and geologic flood causes helped delineate the zones where forest management for flood prevention would be the most effective.

CONCLUSIONS

1. Dans le Nord-Ouest des État-Unis les coupes à blanc et les incendies des forêts ont accentué les inondations, provoquées par des eaux de fonte des neiges, sans la pluie, ou avec la pluie.
2. Dans des cas de réinstallation, avec le temps, de la végétation forestière dans les bassins de réception, les grandes débits (hautes eaux) lors des inondations ont été de nouveau diminués.
3. Dans des bassins de réception avec une constitution géologique de dépôts marins ou de roches volcaniques, l'effet des forêts sur les inondations a été le même.
4. Soit que les conditions atmosphériques, avant et pendant l'inondation, furent sévères, soit qu'elles furent médiocres, l'effet des coupes de bois sur les inondations a été le même.
5. En ce qui concerne des inondations causées par la fonte des neiges, précédée d'une pluie, l'effet de la forêt sur celles-ci a été plus considérable dans la zone située au-dessous du niveau de la fonte de la neige. L'évaluation des raisons météorologiques, topographiques, et géologiques des inondations aide à delimiter les zones, dans lesquelles un aménagement approprié des forêts aurait été le plus effectif.

Flood waters in northwestern United States originate in the mountainous zone of forested and once-forested watersheds (catchments). In managing these lands, foresters are becoming more aware of the importance of their work as it is related to watershed protection and flood prevention. In order to plan their management, they want to know where protection is most needed and what effect forest management—good or bad—has on floods. Flood control engineers in this area, too, need the answer to such questions so they can properly design and locate dams and channel embankments.

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What are the effects of changes in forest and other land conditions on floods—snowmelt floods, rain-on-snow floods, and rain-caused floods? How do the effects vary with elevation, geology, size of watersheds, and size of storm? To seek answers, past floods from 75 watersheds in western Oregon and Washington were analyzed using graphical, multiple regression, and covariance analyses.

These studies were part of the U.S.D.A., Forest Service, Flood Prevention Survey of the Columbia River Basin conducted by the California and Pacific Northwestern Forest and Range Experiment Stations, largely in the years 1950 to 1952.

Methods

Flood causes can be determined by analysis of floods from watersheds with wide differences in meteorological happenings and in topographic and geological characteristics. Variations in these bring about wide fluctuations in flood size. We can hypothesize that differences in forest cover and land management also cause differences in floods, and that the variations in floods attributable to differences in forest and land management will become apparent and measurable when the variation in floods contributed by other causes are isolated.

The studies consisted of four steps: (1) preliminary tests of meteorological variables related to floods and the effects of forests on floods; (2) formulation of the model relating floods to their causes; (3) selection of storms and watersheds for analysis; and (4) analysis of the data by successive refining of variables, by testing joint effects of variables, and by testing differences among groups.

Preliminary Tests

In forming hypotheses of how floods are related to variables of meteorology, topography, and forest cover, we made simple tests using part of the available data. Meteorological variables such as storm intensity and antecedent precipitation, were tested to see which were most closely related to floods of the past. To test forest effects we made graphical tests of floods from watersheds with wide variations in forest conditions during the period of record.

Preliminary Tests of Forest Effects

Simple tests were made of the effects on floods of logging of forested watersheds. In the first test, flood peak discharges of two watersheds were compared, before and after one of them was logged. The 320-square-mile Mollala watershed, and the 665-square-mile Clackamas were used. Both watersheds discharge into the Willamette River near Portland, Oregon. Forests on the Clackamas remained constant in the period 1928 to 1943; whereas 35 square miles of the forest on the Mollala were clear cut.

Twenty-one floods in the Clackamas and Mollala Rivers were compared (Fig. 1), using double mass analysis (Kohler, 1949, Anderson, 1955), starting with relatively little of the forest of the Mollala River watershed logged off, and ending with 35 square miles of the forest logged. The analysis showed that floods were progressively higher in the Mollala—31 per cent higher in the second set of seven floods than in the first seven, and 56 per cent higher

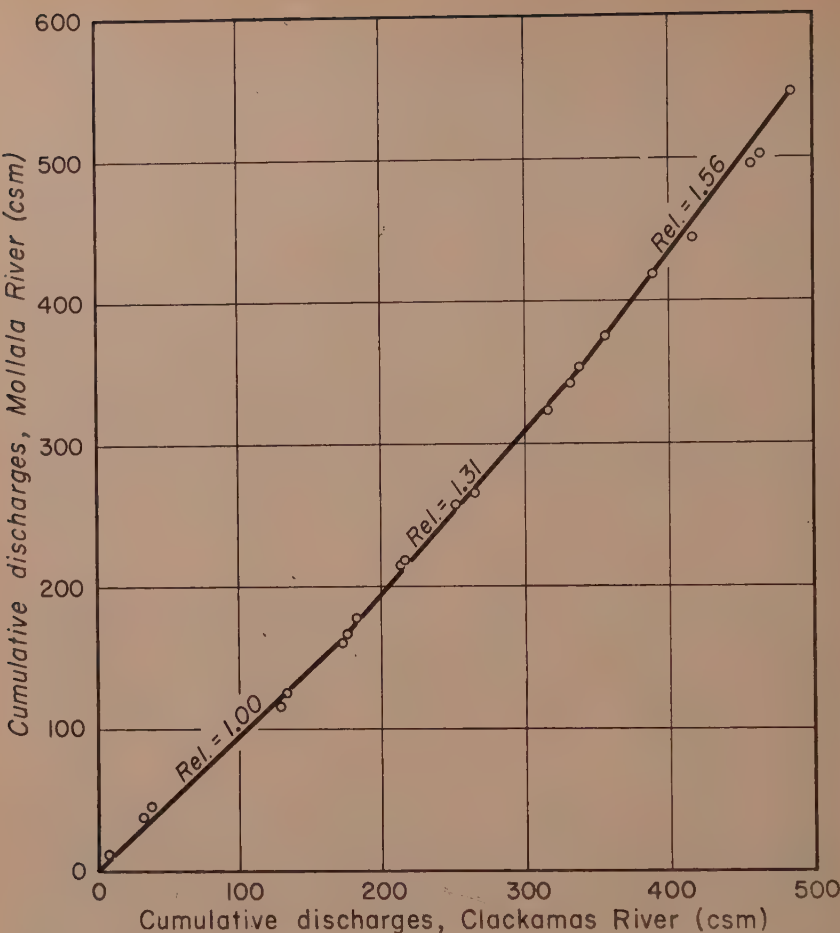

Fig. 1. Flood peak discharges, Clackamas River watershed (unlogged) and Mollala River watershed (logged), Willamette River Basin, Oregon, 1928—1943.

in the last seven floods than in the first. *We infer from this analysis that logging of the forest caused the increase in floods in the Mollala watershed.*

The second simple test of the changes in floods with logging of the watershed was made using the Willamette River above Albany, Oregon, (4,840 square miles) as the test watershed, and a tributary watershed, the McKenzie River (320 square miles), as a control (Anderson, 1950). Floods in the period 1920 to 1948 were compared (Table 1). Some 168 square miles of the forest in the Willamette River watershed had been clear-cut and not reforested in the period, whereas the forests in the tributary McKenzie River were relatively unchanged. Ratios of the annual floods peaks of the Willamette compared to the McKenzie River increased from 14.20 to 1 to 18.41

TABLE 1. — *Comparison of peak discharges, logged Willamette River and unlogged McKenzie River, Oregon.*

Period	Mean annual maximum discharge		Ratio	Increase
	Willamette River	McKenzie River		
	cfs	*cfs*	*W/M*	*per cent*
1920—34	105,100	7,400	14.20/1	—
1935—41	73,100	3,970	18.41/1	30
1942—48	136,600 (1)	8,530	16.01/1	13 (1)

(1) Partly controlled by Fern Ridge and Cottage Grove Reservoirs.

to 1 and then became 16.01 to 1. *The changes indicate (1) a 30 per cent increase in the peak discharges with the increase in clear-cut area in the 1935 to 1941 period as compared with the earlier 1930 to 1934 period, and (2) a persistence of higher flood peaks in the 1942 to 1948 period with floods being 13 per cent higher than expected, despite a partial control of floods by two major new reservoirs.*

These simple tests, and others (Table 4) to be discussed later, suggest that forest cutting has affected the sizes of floods from watersheds. However, whether a forest was cut or not is obviously an inadequate measure of the change in forest condition and probably of the effects on floods. Further specification of just how the forest was cut and how the forest regenerated after cutting is needed by both the land manager and the flood control engineer; more comprehensive tests of the effects on floods of specific changes in forest variables on specific sites in watersheds are needed. Such comprehensive tests require other controls. Meteorological controls seem promising, both as unbiased estimators of floods, and as useful in assigning relative flood potential to land areas.

TABLE 4. — *Changes in peak discharges of watersheds computed from covariance results and by double-mass plotting.*

Watershed	Area	Change in ASE	No. peaks	Change shown by double-mass plotting	Change shown by (1) covariance
	sq mi	*sq mi*		*cfs/flood*	*cfs/flood*
Mohawk	180	8.1	24	790	810
Mollala	323	34.6	10	3,800	3,460
Long Tom	391	15.6	7	1,700	1,560
Willamette	7,280	168.0	7	16,700	16,800

(1) 100 · △ ASE.

Preliminary Tests of Meteorological Variables

Preliminary tests were made of meteorological variables related to floods (Anderson, 1958). We wanted to select those characteristics of storms and antecedent meteorological conditions which would index: (1) rainfall intensity, (2) rain-snow areas in watersheds, (3) wetness of the soil, and (4) ripeness of the snow. Storms were defined as a period of precipitation unbroken by days with less than 0.10 inches of precipitation. Tests were made of which storm-precipitation variables and antedecent wetness variables were best related to floods occurring before and after February 1. For each of three sizes of watershed (100, 655 and 4,840 square miles) a rank correlation analysis was made using combinations of storm and wetness variables—one-, two-, and three-day maximum precipitation and antecedent 30-, 60-, and 90-day precipitation. The results showed no consistent best relation for the different sizes of watersheds so the average of the best combinations was chosen: the 2-day precipitation and the 60-day antecedent precipitation.

In further preliminary tests, the minimum temperature during the storm (as an index of area of rain versus snow), and the antecedent 60-day temperature (as an index of snow ripeness) were found significantly correlated with floods (Anderson, 1958). Later the area below the snowmelt line in watersheds was added as a variable. The first four variables, 2-day precipitation, 60-day antecedent precipitation, minimum storm temperature, and 60-day antecedent temperature were used in selecting meteorological events for final analysis.

Selection of Storms for Analyses—Rain-Snowmelt Floods

Basically, the storm and its associated and antecedent meteorological conditions is the event being studied; the flood is the result. In selecting storms for analysis, the attempt was made to include every combination of small, moderate, and large storm sizes and of the other meteorological conditions. In all, 43 storms were selected for analysis. For each of the storms isopercential maps were drawn for the whole Willamette Basin, expressing maximum 2-day precipitation of the storm as a percentage of the mean annual precipitation. The mean annual precipitation for each elevation zone in each watershed was determined using mean annual precipitation maps of the Corps of Engineers (1950). From these it was possible to estimate the precipitation for any storm in any elevation zone in any watershed. Similarly, the antecedent precipitation to the storm was determined. Temperatures during storms and antecedent to storms was determined from valley station measurements adjusted by using normal lapse rates of temperature with elevations. Thus, the meteorological conditions in any part of any watershed, during or antecedent to each storm could be estimated.

Selection of Watersheds for Rain-Snowmelt Floods Studies

Fifty-four watersheds with a wide variation in size, geology, topography, and land use were selected. All the watersheds were in the Willamette River Basin of western Oregon. They ranged in size from 5.7 to 7,280 square miles; in mean elevation, from 700 to 4,000 feet, and in mean annual precipitation, from 44 to 104 inches. The forests were Douglas fir with some lodgepole pine at high elevations. In general, floods are always associated with rain storms, but melting snow contributes to the flood (Corps of Engineers, 1950). As the measure of flood size from a watershed, the peak discharge for each storm

as measured by the United States Geologic Survey was used when available. When the peak was not given for the storm, it was estimated from the recorded daily discharge by relating other peaks to daily discharge for that watershed. In all, 912 peak-discharge measurements with the associated meteorological and watershed conditions were included in our analysis.

Relation of Rain-Snowmelt Floods to Non-Forest Variables

The model used in the analysis was: flood size is a function of meteorology, topography, geology, and cover (Equation 1, Table 2). Multiple regression was used to isolate meteorologic, topographic, and geologic causes of floods; covariance analysis was used to determine forest effects and the variation in forest effects with watershed size, storm size, and geology.

The definition of variables used and the results of the regression analysis are shown as Equation No. 2, Table 2. All of the variables relating floods

TABLE 2. — *Regression model and results for rain-snowmelt floods and spring snowmelt floods.*

Item		Definitions	
THE MODEL			
(1) Q = M + T + G + C		Meteorology, topography, geology, cover	
RAIN-SNOWMELT FLOODS			
(2) log Q'11	= 1.88	Peak discharge of a storm, cfs	
	+ 0.205 log RA	Rain area, min. temp. > 32° F. sq mi	M
	+ 0.794 log P2	Max. 2-day precip. in rain area, in	M
	+ 0.832 log P60	Precip. in 60-days antecedent, in	M
	+ 0.476 log T60	Temp. at mean elev. in 60 days antec., ° F	M
	+ 0.152 log SM	Area below snowmelt line, T60>27.5 + P60/13.5, sq mi	M
	+ 0.600 log A	Area of watershed, sq mi	T
	— 0.022 NS	North-south equiv. slope (R. E. Horton), pct	T
	— 0.022 UA	Area of unconsolidated alluvium in SM, pct	G
	— 0.016 CA	Area of consolidated alluvium in SM, pct	G
	— 0.019 YV	Area of young volcanics in SM, pct	G
	— 0.015 OV	Area of old volcanics in SM, pct	C
	+ 0.063 log BC	Area in bare cultivation, sq mi	
(3) Q'12	= a	Constant for given watershed	
	+ 1.387 Q'11	Calculated peak discharge from Eq. (2), cfs	
	— 103 ASE	Age-stocking of forest in area SM (From Forest Survey maps), sq mi ASE	C

TABLE 2. — *Continued.*

Item		Definitions	
SPRING SNOWMELT FLOODS			
(4) log Q'8	= 5.07	Peak discharge, cfs	
	+ 0.287 log FR	Fall rain (Oct.), in	M
	+ 0.584 log WR	Winter rain (Nov.—Mar.), in	M
	— 0.890 log WT	Winter temperature (Nov.—Mar., mean), ° F	M
	+ 0.136 log SR	Spring rain (Apr.-flood date), in	M
	— 0.266 log ST	Spring temperature (Apr.-flood date, mean) ° F	M
	— 0.806 log NS	North-south equiv. slope, pct	T
	— 2.261 log PH	Physiographic index of watershed, pct	T
	+ 0.934 log A	Area of watershed, sq mi	T
(5) log Q'9	= — 0.24	Peak discharge, cfs	
	+ 1.068 log Q'8	Calculated peak discharge from Eq. (4), cfs	
	+ 0.045 log PSB	Poorly stocked and burned forest land, sq mi	C

to causes were significant at the 1 per cent level, except the antecedent 60-day temperature (T60) and the area in bare cultivation (BC), which were significant at 5 per cent level. Standard error of estimate of the regression equation was 0.271.

Relation of Rain-Snowmelt Floods to Forest Conditions

To evaluate the effects of forest conditions on floods and test variation in forest effects with watershed size, storm size, and geology, a special sample of watershed and storms was selected and a special forest variable was defined.

The Forest Variable: Cover before and after cutting was expressed by two characteristics of the forest: age and stocking. To the forest manager, age and stocking of the forest define the amount and condition of the growing stock; to the hydrologist, these characteristics are expected to affect floods because of their effects on water losses, protection of the soil, and snow conditions. The forest variable, age-stocking-effectiveness (ASE), was the product of a weighted age-effectiveness and of stocking for individual units of the forest in watersheds. Age and stocking were taken from forest maps (Pacific Northwest Forest and Range Experiment Station, 1947); age-effectiveness was taken proportional to foliage increase with age (Kittredge, 1948) as follows: zero for age zero, 0.3 for age 10 years, 0.7 for age 20 years, and 1.0 for ages 30 years and greater. Thus a forest stand with 55 per cent stocking, 20 years of age had age-stocking-effectiveness of 0.55 × 0.7) or 38 per cent. The average forest conditions in that watershed at the time of the flood was the area-weighted average of the age-stocking-effectiveness for those parts of the watershed where rain was falling or snow melting.

Fourteen watersheds with at least 10 per cent change in the forest age-stocking-effectiveness during the period of discharge records were available

for study. In twelve of these the age-stocking-effectiveness had decreased during the period of record, in two the age-stocking had increased during the period of flood measurements.

Four storms were selected for each watershed, a small storm and a large storm when the forest age-stocking was high, and a small and a large storm when the forest age-stocking was low. As a meteorological control, the potential of each storm, Q'll, based on the eleven variables of Equation No. 2, Table 2 was calculated. The forest age-stocking in the zone below the "snowmelt line" for each of the four storms was determined. Flood size was related to the forest age-stocking-effectiveness and to the meteorological control, Q'11, by analysis of covariance.

The within-regression coefficients from the analysis of covariance were taken as the best measure of forest effects on floods. This, in effect, averages the forest effects on floods in 14 watersheds. The result is shown in Equation No. 3, Table 2. The regression coefficients for both the meteorological control variables, Q'11, and forest age-stocking-effectiveness, ASE, were both highly significant. *The regression coefficient for forest age-stocking indicates that clear cutting one square mile of forest in the area below the snowmelt line for a given storm will increase the flood peak 103 cubic feet per second.*

Other Tests

Covariance tests were made to answer other questions. Was the variable "area logged" as good an expression of forest effects on floods as the age-stocking-effectiveness variable? Age-stocking was better: the regression coefficient was more significant than that for the simple variable of "area logged". Also, the "area logged" variable could not indicate recovery from logging, as in the two watersheds in which age-stocking had increased rather than decreased during the period of flood records and a corresponding decrease in floods occurred.

Covariance analyses were made to test the effect of cutting a forest in the coast mountains, where marine sediments predominate, versus cutting a forest in the Cascade mountains, where volcanic geology predominated. The regression coefficients for the forest effects on floods were nearly identical for these two groups, therefore, we conclude that forest effects on floods did not vary appreciably with these broad geologic types.

Similar tests were made of the forest effects as they vary with storm size. The joint variable of storm size, Q'11, and forest-age-stocking, did not add significance to the covariance test; therefore, there was no indication that forest effects on floods were different for different sizes of storms.

The applicability of a log transformation of the data was tested but dropped because such transformation did not allow rational extrapolation of forest effects to forest conditions widely different from those in the watersheds studied. Another transformation in which the log of the peak discharges was related to age-stocking to the 1.5 power seemed promising in removing the distortion of a general log transformation and gave a more valid estimate of forest effects for all watersheds. However, it was concluded (1) that the present state of knowledge suggests use of Equation No. 3 for estimating forest effects on floods in western Oregon, and (2) that more studies are needed so that the flood runoff from each forest and topographic site can be more consistently predicted.

TABLE 3.—*Rain and snowmelt frequency, relative precipitation and flood potential by elevation zones, Willamette River Basin above Salem, Oregon.*

Elevation, feet	Relative rain area frequency	Relative snowmelt frequency	Relative precipitation	Relative flood potential
0—1,000	1.00	1.00	1.0	1.0
1—2,000	.96	.99	1.5	1.5
2—3,000	.87	.92	2.1	1.9
3—4,000	.74	.82	2.4	1.9
4—5,000	.60	.74	2.4	1.7
5—6,000	.39	.48	2.4	1.0
6—7,000	.17	.38	3.1	0.6

Applications

How do flood potentials vary with elevation and geology in the watershed areas? The regression results (Equation No. 2, Table 2) were used to answer this question. For the 65 larger storms in a 65-year period, Table 3 shows the proportion of events in which each elevation zone was contributing to floods because that zone was in the rain area or in the snowmelt area for these storms. Notice the high flood potential of the 2,000- to 4,000-foot elevational zone, where both rain and snowmelt are common. These results point to areas where care in land management may be most needed and most effective.

In other studies the flood potentials from Equation No. 2 have been used to estimate sediment production from various zones in watersheds (Anderson, 1954).

By way of final check of forest effects on floods, the results from these covariance tests were compared with graphical tests. The results of five such tests shown in Table 4 are surprisingly close. However, double-mass tests would not predict recovery from cutting as would the covariance results, nor would they show the different effects on floods of forest cuttings in various elevation zones.

Spring Snowmelt Floods

Another analysis was made to test the effects of forest cutting and burning of forest lands on floods which were primarily due to spring snowmelt. These tests were made in areas on the east slopes of the Cascade mountains in Washington and in the Blue and Wallowa mountains of northeastern Oregon. In both areas, annual precipitation is as much as 50 inches at the higher elevations, much of it falling as snow.

The forests are ponderosa pine at lower and middle elevations. In the higher mountains, the forest is a mixture of ponderosa pine, larch Douglas-fir, Engelmann spruce, and lodgepole pine. Before 1940, most logging was of the largest ponderosa pine. After 1940, the demand for timber increased, logging moved farther back in the forested areas, and all species are now harvested. As much as 50 per cent of the forest land in some areas is understocked as a result of logging and fire.

Regression and covariance analyses were made to determine the effects, on these snowmelt floods, of various watershed variables and forest cutting and burning.

Meteorological and Watershed Causes of Snowmelt Floods

A multiple regression analysis was made using the flood peak discharges from 21 watersheds over a period of 30 years of streamflow recording. Fifty-seven floods in all were used to determine the relation of flood size to these watershed and meteorological conditions: The fall precipitation during a year was used to provide an index of the ground water conditions affecting floods. Precipitation during the winter was taken as an index of the moisture accumulation in the snowpack. The amount of moisture accumulated is affected by the losses from the snowpack through melting and sublimation; temperatures during the accumulation period was used to index such losses. As a measure of the melt potential, the precipitation and temperature near the end of the nominal snow season was used. Watershed basin characteristics affecting floods were indexed by the drainage area, by the north-south component of slope (Horton, 1945), which is a single-valued expression of watershed slope and exposure, and lastly by a physiographic index of drainage.

Relationship of peak discharges to the watershed and meteorological variables is given by Equation No. 4, Table 2. All variables in the equation were significant. The standard error of estimate was 0.232.

Results of Equation No. 4 were used to compute a non-forest flood potential for each storm and watershed. This non-forest flood potential, Q'8, together with a forest variable, "area of poorly stocked and burned over forest land", were used in covariance analysis regression. The results were given by the "within watershed" regression Equation No. 5, Table 2. Both the flood potential variable and the forest variable were significant. The standard error of the equation is 0.232 log units. Snowmelt floods are increased by about 11 per cent when one-half of the forest in the watershed becomes poorly stocked or is burned.

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FROST AND FOREST SOIL

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SUMMARY

Average depths of concrete frost and its percentage occurrence in 14 forest-condition classes in the Northeastern states are presented and compared with frost observed in four open-land use conditions. Observations in the various conditions were taken bi-weekly during two winters, 1950—52, in each of six areas ranging in location from central Maine to northern Pennsylvania. Statistical significance of differences in concrete frost depth among forest conditions, among open-land conditions, and between forest and open-land conditions are given. Results are interpreted in light of recent findings on time of soil freezing and thawing in the Northeast, on recent ring infiltrometer tests of concrete frost in forest and open-land, and on past observations of surface run-off from frozen soils. The effects of climatological and soil differences between forest and open-land conditions are discussed in respect to frost occurrence and persistence.

RÉSUMÉ

Les profondeurs moyennes de sols gelés imperméables à l'eau et les pourcentages de leur production dans 14 endroits dans les forêts des États du Nord-Est sont présentées et comparées avec la gelée observée dans quatre endroits, situés en plein champ

Des observations ont été faites deux fois par semaine, pendant deux hivers, 1950—1952, dans chacune des six régions choisies du Central Maine à la Pennsylvanie du Nord. On donne la signification statistique des différences des profondeurs des sols gelés imperméables à l'eau entre les conditions forestières, entre les conditions en plein champ et entre les conditions forestières et de plein champ. Les résultats sont interprétés à la lumière 1) des trouvailles récentes sur les temps de la gelée du sol et de leur dégel dans le Nord-Est, 2) des mesures récentes à l'infiltromètre des sols gelés imperméables à l'eau en forêt et en plein champ et 3) des observations plus anciennes de l'écoulement de sols gelés. Les influences des différences climatologiques et pédologiques entre les conditions forestières et de plein champ sont discutées en considération de la production et de la persistance de la gelée.

Frost in forest soils results from the action of below-freezing temperatures on soil moisture. Some of its effects have been enumerated by Sakharov (1945): it contributes to soil formation and affects soil structure; it increases moisture in the upper horizons; it stimulates soil animals to migrate to greater depths; it increases wind stability of forest vegetation; it delays the beginning of spring growth; it slows litter decay, humus formation, and chemical and microbiological processes; it improves operating conditions for timber harvesting; and it can decrease soil permeability.

Of these several effects, none has more far-reaching influence than the effect of frost on soil permeability. For it is this effect that may be responsible for damaging flood peaks resulting from weather conditions that have produced simultaneously impermeable soil frost, melting snow, and possibly rainfall.

Certainly, no aspect of frost is less understood than this complex relationship. A measure of our understanding is lack of factual evidence as to how and when and where frost has been a cause of floods. Opinions are contradictory. Colman (1953), for instance, has stated that:

"... Soil freezing is occasionally responsible for flood flows and other high rates of stream discharge in those parts of the United States where low winter temperatures prevail, when the snow cover is light, and where unusual spring conditions bring rapid snow melt and rain... Spring floods on the Upper Missouri River and from there eastward to new England have sometimes been augumented by the flow of water over the surface of frozen soil. And in the Palouse region of eastern Oregon and Washington, soil freezing plays an important part in the generation of high runoff flows in late winter and early spring."

Hoyt and Langbein (1955) have a different interpretation:

"By preventing infiltration of water, frost in the ground may aggravate floods in winter or early spring, but the effect is not as serious as is often supposed. First, snow itself is good insulation and an early snow effectively protects the ground. Moreover, infiltration is generally low at such times anyway because the absorptive capacity is lowered by the high moisture charge that is built up during the winter and early spring. Further, not all frost inhibits infiltration. Frost that has a porous granular structure has a relatively high absorptive capacity; only frost that is massive, sometimes called 'concrete,' prevents absorption of snowmelt."

These contrary views pertain, of course, to all lands, both open and forested. But since much of the area in the frost region is in trees (New England, for instance, is 77 per cent forested), they have particular pertinence to forest conditions.

The purpose of this paper is to review briefly the status of our knowledge of forest soil frost (based largely on work in this country) and to present the findings of a recent frost survey in the Northeast.

Frost Formation

Freezing is the process in which ice crystals are formed from liquid water. Garstka (1945) has described its results as follows:

"Since ice is not wet, freezing results in a drying out of the soil... (and) tends to translocate water from one level to another. The formation of ice in the frozen soil sets up a capillary tension which sucks water from the horizon below it. As this water reaches the frozen layer, provided there is a deficiency of heat sufficient to absorb its latent heat of fusion, this water likewise freezes and thus the capillary tension is permitted to continue. The building up of these layers of ice results ultimately in what are known as 'ice-lenses'. Surface-layers of the soil thus acquire volumes of water far beyond that which they are able to hold against the pull of gravity under frost-free conditions."

Concentration of moisture at or near the soil surface is characteristic of frozen soil. This increase may be as much as 20 to 30 per cent by weight (Kittredge, 1948). Post and Dreibelbis (1942) found moisture contents of frozen silt loam to range between 23 and 213 per cent while that of unfrozen soil beneath ranged in most cases, between 25 and 40 per cent. Tigerman and Rosa (1949) found near-saturation moisture contents of 40 to 46 per cent for frozen clay loam to clay soils; clay and shale beneath the frozen layer

contained only 13 per cent. In central New England, Goodell (1937) noted that the water equivalent of a snow blanket 30 to 36 inches deep was held as ice in frozen soils, specifically, between 3.0 and 5.6 inches of water. Anderson (1947) found that surface soil freezing drew water from depths as great as 36 inches in a gravelly sandy clay loam. Chirrikov and Malugin (1926) reported that once the surface soil became frozen the lower soil layers dried out during the winter as a result of contributing moisture to the frozen soil above.

Frost Types

Freezing can produce a variety of frost types. The three most common are concrete frost, which usually penetrates the soil several inches and is impermeable to water; honeycomb frost, which is shallow and loose in structure; and the descriptively-named stalactite frost formed when quick freezing of wet soil projects small icicles above the soil surface (Post and Dreibelbis, 1942). Other intermediate frost types have been reported.

As yet, little is known about the conditions under which different frost types are produced. Byrnes (1951) found that concrete frost is formed at temperatures below 30° F., and the larger crystals of honeycomb frost tend to be associated with high organic-matter content. Taber (1930) and Beskow (1935) found when soils freeze rapidly a granular type of frost results; conversely slow freezing encourages the growth of ice crystals and tends to create the concrete type of structure.

Frost and Vegetation

The presence or absence of vegetation or kind of vegetation markedly influence time of frost formation, depth of its penetration, and when it disappears. Table 1 gives a summary of some findings. Differences in frost depth, as exemplified in this table, may not be so significant in regard to runoff as day-differences in incidence. Sakharov (1945) has pointed out that depth of frost does not markedly influence its permeability.

Much of the effect of vegetation may be related to differences in litter depth. Kienholz (1940) found that under accumulation of leaves in depressions the frost barely penetrated the mineral soil, whereas where wind had swept most of the leaves away, frost penetrated into the mineral soil nearly as deep as in a plowed field; layers of hardwood leaves and pine needles were about equally effective as insulators. In a Russian study, removal of litter from aspen-basswood plots resulted in frost penetration of 35 cm. as compared to 5-cm. penetration in undisturbed plots; 1 year's leaf fall noticeably decreased frost depth (Sakharov, 1945). In the Northeast continuous frost was found to a depth of 3 inches in a hardwood plot with litter removed as compared to a depth of a few tenths of an inch, and that for 2 days only, on an undisturbed plot; comparable values from white pine plots were 8 and 3.5 inches (Storey, 1955). Maximum frost penetration in a 28-year-old plantation of red and white pine was 5.8 inches under litter and 8 inches where litter was removed (MacKinney, 1929).

Snow Depth and Other Influences

Snow depth and aspect also have important effects on frost formation. Goodell (1939) found freezing considerably deeper on north-facing than south-facing slopes.

TABLE 1 — *Some research findings on the relation of frost incidence and depth to vegetation.*

Location	Vegetation	Depth of frost pene-tration	Difference in appearance or dis-appearance of frost from open land		Reference
			Appear.	Dis-appear.	
		Inches	*Days*	*Days*	
New Hampshire	Open field	15	—	—	(Belotelkin, 1941)
	Hardwoods	5	—	0	
	Spruce flat	15.7	—	23	
	Spruce swamp	19	—	43	
Connecticut	Open field	10.1	—	—	(Kienholz, 1940)
	Mixed hardwood	5.1	21	—5	
	Red maple	4.1	31	0	
	White pine	2.9	44	13	
Northeast	Open field	—	—	—	(Sartz, 1957)
	Hardwoods	—	35	—5	
	Softwoods	—	14	10	
Vermont	Open area	—	—	—	(Burns, 1944)
	White pine	—	26	16	
	White pine (thinned)	—	10	25	
Illinois	Corn field	5.5	—	—	(Goodell, 1939)
	Pasture	1.5	—	—	
	Hardwoods	.0	—	—	

The effect of snow also depends on its depth. In New York, a depth of 17 to 31 inches prevented soil frost in a forest when average minimum temperature was 7° F. In a bare field nearby with 7-inch snow cover, the soil froze to a depth of more than 30 inches. On another field, a snow depth of 58 inches prevented soil freezing, and depths of 10 to 17 inches prevented freezing in abandoned fields with herbaceous cover (Spaeth and Diebold, 1938). At high elevations in Utah, frozen soil in open range was found wherever the depth of snow was less than 18 inches (Tigerman and Rosa, 1949). In open land in Wisconsin, 24 inches of snow prevented frost penetration at —21° F.; 18 inches of snow prevented frost penetration at 12 inches with weekly average minimums of —11 and —13° F. but did not prevent frost penetration to this depth at —21° F. (Bay et al., 1952).

Compactness of snow also influences frost; the more compact, the greater the freezing (Sakharov, 1945). Belotelkin (1941) observed that even slight trampling of snow affected frost depth.

Frost Thaw

Surmach (1955) has described the diurnal rhythm involved in thawing as one of day-time downward movement of free water melted by the sun's warmth followed by upward movement of water during night freezing. Where frost is snow-covered, the soil may not thaw to a depth to permit percolation downward, and consequently the water may run down slope. Frost thawing takes place from below as well as above so that at the end of the frost season the frost remnants may lie midway between the surface and deepest penetration (Scholz, 1938; Kienholz, 1940; Belotelkin, 1941; Bay et al., 1952).

The amount of thaw within a forest stand at any time is rather variable and responsive to micro-relief and variation in shading and soil characteristics. Jaenicke and Foerster (1915) noted that, when frost had disappeared from the ground on the south side of trees, there remained 13 inches of frozen soil on the north side and 21½ inches in openings. Belotelkin (1941) also observed that 3 to 10 days before the last vestige of frost had disappeared, patches of no-frost could be found that would provide channels for infiltration of water. Thus dates of last frost in the ground and, perhaps, dates of first frost have little significance to surface runoff unless its areal distribution and, of course, type are identified.

Effects of vegetation on time of thaw are evident in table 1. Open land soils thaw before softwood soils but after hardwood soils. Reasons for the differences, as Sartz (1957) points out, are not completely understood and probably involve differences in heat exchange derived from canopy differences. Aspect and snow also affect frost thaw: soil frozen to a considerable depth can thaw under a snow cover of 30 or 40 inches, and frost has been observed to emerge a week earlier on southerly than on northerly slopes (Kienholz, 1940).

Frost and Runoff

The effect of frost on runoff depends on the type of frost, its distribution in space, and its occurrence in time in respect to weather conditions that produce either melting snow, rainfall, or both.

Honeycomb and stalactite frosts are permeable and may even be more permeable than frost-free soil. Concrete frost, whether in the open or forest, is impermeable except where it is penetrated, in the forest, by frost-free passageways (Trimble et al., 1958).

The effect of different frost types can be judged from observations by Belotelkin (1941):

"Moisture present in the litter, humus, and upper layers of the mineral soil formed snow-like crystals enabling the soil to maintain a good degree of permeability far into the winter. Soils in the open field, on the other hand, began freezing solidly for several days at a time.

Observations made during and after a heavy rain . . . illustrate the effect of different types of freezing on runoff. Before the rain, freezing in the open field had reached a depth of four inches, in the spruce swamp 2.5 inches, and in the spruce flat 1.5 inches whereas in the open the rain of 1.78 inches thawed only one-fourth to one-half inch of the soil-surface, with no thawing whatsoever occurring on the level portions of the site. Under the forest-canopies most of the frost left the ground. What frozen patches remained in the forest were saturated with freely moving water. In the open

field, water remained standing in slight depressions or ran freely along the slope. Under the forest-cover no traces of free water were observed on the surface during or after the rain."

Trimble, Sartz, and Pierce (1958) have pointed out that concrete frost in the forest is apt to be less widely distributed than in open fields so that any water running off concretely frozen areas may go but a short distance before reaching and infiltrating unfrozen soil.

Measurements at Cohocton, N. Y., in small cultivated watersheds revealed direct relationships between frost area and runoff: where 25 per cent of the area contained frost, runoff was 12 per cent of total rainfall and snow melt water; frost of 63 per cent gave 41 per cent runoff; and 93 per cent frost gave 53 per cent runoff (Storey, 1955).

Perhaps the best example of the frost-snow melt-rainfall-vegetation relationship for a flood period are the data from the Arnot Forest at Ithaca, N. Y., during the 10—19 March 1936 flood period. Previous to this period a 20- to 30-inch snow cover in the forest had prevented soil freezing (air temperatures had been as low as —18° F.). In the open fields, which were bare of snow or only lightly covered, soil was frozen to a depth of 30 inches. On bare plots with 8 inches of snow and receiving 6.57 inches of rainfall, runoff was 7.87 inches. Bare plots whose snow had melted from 60 to 42 inches during the period had 0.64 inches runoff. Forest cover with 19 to 12 inches of snow had 0.02 inches runoff (Soil Conservation Service, 1939).

Frost and Erosion

Considerable erosion may be associated with runoff from frost; or if frozen areas are well vegetated, as at the Arnot Forest, no soil loss may occur (Soil Conservation Service, 1939).

Widespread erosion from the combined effects of snowmelt, frozen ground, steep slopes, and poor vegetal cover were observed by Tigerman and Rosa (1949) in northern Utah. As frost melted in the upper layer, saturated soil moved downslope over the frozen layer as mud flow. Rill erosion was also produced when free water, running over frozen soil, picked up soil particles.

Bay, Wunnecke, and Hays (1952) have observed that when rain and thawing occurred at the same time, runoff and soil losses were greater than from thawing alone. A thaw with 2 inches of snow gave a soil loss of 0.21 tons per acre whereas a thaw plus 0.66 inch rainfall gave a loss of 0.94 tons per acre from winter wheat runoff plots.

The tendency of frost to reduce soil stability (Slater and Hopp, 1949; Domby and Kohnke, 1955) by breaking down soil aggregates may be responsible for greater surface runoff and erosion after frost has disappeared.

Frost Survey in the Northeast

To determine the distribution of concrete frost in various land-use and forest conditions, a frost survey was made in east-central Maine, east-central New Hampshire, northern New York, southern New York, northwestern Massachusetts, and northeastern Pennsylvania during the winters of 1950—51 and 1951—52 (Pierce et al., 1958).

At each area 12 to 17 land-use conditions were selected for study, covering a range of 18 conditions in all. Four of the conditions were open

TABLE 2 — *Average frost depth, occurrrence, and accumulated depths for all areas*

	Land-use condition	Frost: Depth	Frost: Percentage occurrence	Frost: Accumulated depth	Areas represented
		Inches	*Per cent*	*Inch-days*	*No.*
	HIGH FROST INTENSITY				
1.	Bare cultivated	6.2	80	553	6
3.	Good pasture	5.2	69	408	6
2.	Hayland	4.9	71	382	6
4.	Poor pasture	4.7	57	307	4
	INTERMEDIATE FROST INTENSITY				
15.	Hardwood sawtimber (grazed)	3.4	41	158	3
8.	Coniferous plantation (12—18 years)	3.5	44	151	5
12.	Coniferous poletimber (well stocked)	3.5	41	150	6
16.	Coniferous sawtimber (well stocked)	2.9	36	112	6
17.	Coniferous sawtimber (logged)	2.9	33	95	5
7.	Clear-cut, no reproduction	3.4	32	74	5
9.	Coniferous plantation (30—35 years)	2.6	25	68	4
6.	Hardwood reproduction (clear-cut area)	2.5	17	52	3
5.	Hardwood reproduction (abandoned farm)	2.6	39	51	6
	LOW FROST INTENSITY				
11.	Hardwood poletimber (poorly stocked)	2.5	20	27	3
14.	Hardwood sawtimber (logged)	1.6	20	21	5
10.	Hardwood poletimber (well stocked)	1.7	18	17	5
13.	Hardwood sawtimber (well stocked)	1.4	19	16	5
18.	Coniferous-hardwood sawtimber (well stocked)	1.2	12	10	2

land: bare cultivated, hayland, good pasture, and poor pasture; three consisted of abandoned or clear-cut land; two conditions were coniferous plantations one 12 to 18 years old, the other 30 to 35 years of age; three were in either coniferous or hardwood poletimber of different degrees of stocking; the remaining six conditions consisted of coniferous, hardwood, or mixed sawtimber in various degrees of stocking and use (table 2).

Twice weekly, frost and snow data were recorded at two plots within each land-use condition. Frost type, frost depth in each soil layer, and litter and humus depths were recorded. Depth of concrete frost was measured to a maximum depth of 10 inches. Measurements were taken at the plots about 35 times during each of the two winter seasons.

Average frost depth (for the times frost occurred), percentage occurrence (days of frost occurrence/number of observations during frost period), and accumulated depth (average frost depth x days of frost x percentage occurrence) for all areas are given in table 2. Using accumulated depth as the best indicator of frost conditions, land-use conditions were ranked in descending order of incidence. Conditions fall into three groups: 10 to 27, 51 to 158, and 307 to 553 inch-days. In terms of average frost depths these groups span frost depths of 1.2 to 2.5, 2.5 to 3.5, and 4.7 to 6.2 inches, respectively. Percentages of occurrence overlap slightly, ranging for the three groups in the same order—12 to 20, 17 to 44, and 57 to 80 per cent.

Results of this study suggest several management measures. For instance, the greater prevalence of frost in open lands suggests that abandoned lands should be given fire protection and permitted to revert to hardwood brush or planted to hardwoods as soon as possible. Planting of conifers cannot be recommended as a means of ameliorating soil freezing. Where frost control is a primary management objective, established conifer plantations should be thinned to provide deeper snow accumulations, and invasions of hardwoods should be encouraged. Likewise, any forest treatment or use that reduces litter and humus depth should be discouraged; i. e., fire, grazing, and heavy cutting. Light logging, on the other hand, apparently has little effect on frost.

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MANAGEMENT OF FOREST STANDS IN WESTERN UNITED STATES TO INFLUENCE THE FLOW OF SNOW-FED STREAMS

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SUMMARY

The coniferous forests of western United States influence the regimen of snow-fed streams by affecting the accumulation of snow and its rate of melt. The coniferous canopy absorbs solar radiation that would otherwise be reflected back to space by the snow surface. Much of the absorbed radiation is released as convective heat to the air and warms the environment. In forest openings, this heat may be augmented by direct solar radiation, with the result that snow in unshaded forest openings melts 20—30 per cent faster than does snow shaded by the forest.

The coniferous canopy also intercepts snow and holds it where it is exposed to more intense solar radiation, both direct and as transformed by the coniferous foliage. A dense forest canopy may, in this way, cause the loss through vaporization of up to 30 per cent of the annual snowfall.

Many studies in natural stands on partially cut plots and on small watersheds show that both the deposition of snow on the ground and the rate of melt are inversely related to the canopy density. This means that when canopy density is reduced, snow accumulation and annual streamflow is increased, but the rate of snowmelt is increased so that the spring freshet comes and goes earlier.

Deficient water supplies in western United States give rise to desires to manage forests so that water yields are increased and the high rates of discharge that accompany snowmelt are delayed as much as possible. Under present knowledge limitations, this requires a compromise consisting of maintaining the lowest level of forest density that will shade the snow surface during the seasonal and daily periods when melt rates are highest. General suggestions are made as to how this compromise may be effected; also how forest management may be used to ameliorate the hazard of snowmelt floods.

RÉSUMÉ

Les forêts de conifères de l'ouest des Etats Unis influencent le régime des cours d'eau alimentés par la fonte des neiges en affectant l'accumulation de la neige et le taux de sa fusion. Le feuillage de conifères absorbe la radiation solaire qui, sans cela, serait réfléchie dans l'espace par la surface de la neige. Une bonne partie de la radiation absorbée est transmise à l'air par convection et réchauffe le milieu ambiant. Dans les espaces ouverts de la forêt, cette action peut être augmentée par la radiation solaire directe, avec le résultat que la neige de ces espaces non ombragés fond 20 à 30 % plus rapidement que ne le fait la neige protégée par la forêt.

Le feuillage des conifères intercepte aussi la neige et la retient là où elle est exposée à une radiation solaire plus intense, qu'elle soit directe ou transformée par le feuillage des conifères. Un feuillage dense peut causer, de cette façon la perte par vaporisation d'une quantité pouvant atteindre jusque 30 % de la chute annuelle de neige.

De nombreuses études sur des surfaces dégarnies de leurs arbres et sur de petits bassins-versants montrent que le dépôt de neige sur le sol et le taux de la fusion sont tous deux inversément reliés à la densité du feuillage.

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Ceci signifie que lorsque la densité du feuillage est faible, l'accumulation de la neige et l'écoulement annuel sont augmentés, mais le taux de fusion de la neige est augmenté de telle façon que les hautes eaux printanières se produisent plus tôt.

Les disponibilités en eau insuffisantes de l'ouest des Etats-Unis ont donné naissance au désir d'aménager les forêts de façon que la rétention de l'eau soit augmentée et que les taux élevés de l'écoulement qui accompagnent la fonte des neiges soient réduits autant que possible.

Dans la limite des connaissances actuelles, ceci exige un compromis consistant à maintenir la plus faible densité de forêts qui ombragera la surface de la neige pendant la période où les taux de fonte de neige sont les plus élevés. Des suggestions générales sont faites au sujet de la réalisation de ce compromis, ainsi que sur la façon dont l'aménagement de forêts peut être utilisée pour améliorer les caprices des crues dues à la fonte des neiges.

The accumulation and duration of winter snow are inversely related to the heat supply. In western United States the heat supply to melt or vaporize snow comes predominantly as solar radiation. Both winter and spring are characterized by clear weather, frequently but briefly interrupted by storms. Warm or moist winds bringing advective heat are localized and rare. Under these conditions, coniferous forests significantly affect both the accumulation of snow on the ground and the rate of melt. In turn, this means that such forests influence the amount of flow in snow-fed streams and its seasonal timing. Deciduous forests have less influence. Only coniferous forests will be discussed here.

Forest effects are real and strong, but quantitative information is too incomplete to allow the specification of forest management practices to attain given streamflow objectives. The evidence is both theoretical and empirical and to the extent that it exists is generally in harmony. The deficiencies are in basic data to test hypotheses and in the field testing of practices that theory suggests. Contributing to the first deficiency is a lack of suitable instruments.

This paper will present: (1) some concepts of the physical relationships between forests and snow, (2) some of the stronger evidence that forest management can, through these relationships, affect the disposition of snow, (3) general conclusions on how forest management may be used to attain certain stream management objectives.

Basically, forests influence snow by being absorptive and retentive screens for both solar radiation and falling snow itself. The vaporization of snow is affected, also its rate of melt.

Solar Radiation

Coniferous forests are highly absorbent of solar radiation. The dense shade they cast is caused mainly by absorption of sunlight and only slightly by reflection. To quote from *Miller* (1955) who has made a comprehensive study of forests, snow and climate in the Sierra Mountains of California: "The forest stands out, dark in the landscape, a porous, absorptive region that retains within itself . . . a half or two-thirds of the solar radiation incident upon it."

Only about 5 per cent of the radiation received is reflected back into space from the coniferous canopy. Around 10 per cent is utilized by the trees for transpiration and photosynthesis. Much of the remainder is absorbed and serves to warm the needles, twigs, and branches. The amount penetrating

a canopy to the surface beneath may be as little as 5 per cent of the amount received (*Brecheen*, 1951). It is inversely proportional to the three-dimensional density of the forest cover. Of the amount that does penetrate, some consists of visible wave-lengths that are mostly reflected from a fresh snow surface. This reflected light is again subject to interception by the forest where it is absorbed in part and returned as long-wave energy to the snow or air.

The energy absorbed within the crowns is not lost from the environment but is mainly retained within it in one form or another. Some is re-radiated from the warm foliage as long-wave radiation that is readily absorbed by a snow surface. More is conveyed to the air and, by convection, raises the air temperature of the vicinity. *Miller* (1955) estimates that during a clear winter day in the Sierra Mountains sufficient heat is convected from the forest canopy to raise by 14° C the temperature of a layer of air 100 meters thick. In spring, the estimated effect is considerably greater. No similar estimates for other regions are known and these values from the Sierras may not be typical in magnitude for other landscapes with different forests, topography, and weather. However, they are probably indicative of forest effects in other regions where clear weather is common during winter and spring.

The convective heat from the forest canopy is effective over the landscape generally, in forest openings as well as directly under the canopy. Added to this heat, in unshaded openings, is directly incident solar radiation that is only partly off-set by out-going radiation from snow to sky. The balance, according to *Miller* (1955) results in unshaded forest openings being comparatively hot spots in the landscape. He estimates that at mid-day in clear, winter weather the snow in such openings is subject to 65 per cent more heat than is forest-shaded snow. The difference is even greater in spring when the lowered albedo of the snow makes the direct sunlight more effective. This gain in heat by openings is partially compensated by the greater heat loss from the open areas during the night that results in lower snow temperatures or the freezing of melt water in the snow to form crust.

When coniferous needles fall to the snow surface they continue to exert at least a minor influence on the heat input to the snow through lowering its albedo. This effect is noticeable in spring after melting has caused a concentration of needles and other litter on the snow surface. The author has photographed distinct depressions in the snow surface caused by the melting of snow around individual fascicles of pine needles. The litter accumulation directly under trees is greater than on the snow within openings. The quantitative effect of such litter on the respective albedos of snow under the forest and that in openings is unknown but it must, to some extent, reduce the difference in heat supply to the two areas.

Essentially then, coniferous forests act as a trap for solar energy that would, during the presence of a snow cover and in the absence of forest, be returned to space without effect on the local environment. The total supply of available heat appears to be increased by the forest, but strong contrasts in supply are also created if unshaded openings exist.

Empirical evidence, to the extent that it exists, generally supports the reasoning and basic data referred to. Such evidence is derived mainly from periodic measurements of the snow pack under the forest and in openings. Through these the melt rate is evaluated.

There are no known comparisons between rates of melt within a forested area and within a comparable area that is assuredly free of forest effects on

climate. Perhaps the closest approach to such a comparison is that furnished by a watershed study made near Wagon Wheel Gap, Colorado in a climate where most streamflow originates in snowmelt (*Bates* and A. J. *Henry*, 1928). Following eight years of comparison between two watersheds with respect to climate and streamflow, one watershed, 81 hectares in area, was cleared of the sparse stand of coniferous and deciduous timber that it supported. During seven subsequent years, the beginning of the spring rise of the stream averaged 12 days earlier than before the clearing. This would indicate that the forest removal had increased the heat supply rather than reduced it. However, the area was probably still too small to be free of the effects of surrounding forest. Neither was the original forest typical of coniferous forests in the western United States.

A greater rate of snowmelt in forest openings than directly under the forest canopy has been established by many observations in several states including Idaho (*Connaugthon*, 1935), Colorado (*Wilm* and E. G. *Dunford* 1948), and California (*Kittredge*, 1953). In general it has been found that snow in the shade of a forest canopy melts only 70 to 80 per cent as fast as does unshaded snow in forest openings. It has further been found that the rate of melt is directly proportional to the amount or duration of shade. In Colorado, a comparison was made between two adjacent forest stands in which harvest cutting had cleared half of the ground area of each. In one, the clearing took the form of circular openings about one tree height in diameter. In the other, the clearings were in strips one tree height in width and 8 times as long. The melt rate was less in the stand with circular openings because of the continuous shading. On other test plots (*Goodell*, 1952) the melt rate was slightly higher where thinning had reduced the basal area of a stand to 8.2 sq meters per hectare than where the residual basal area was 10.5 sq meters per hectare. On all thinned plots the melt rate was about one-third greater than on comparable unthinned plots having a basal area of 20.5 sq meters per hectare.

Current research in California (*Anderson* and others, 1958) is directed toward determining on what parts of forest openings snow is retained longest in spring. The results express differences in accumulation depths as well as differences in melt rate. However, on June 1, the most snow is found on the southerly sides of the openings, where the forest shade is most effective.

As early as 1912, *Church* (1912) concluded that the optimum forest pattern for conserving snow was one that included small openings about one tree height in diameter. There seems little reason to change that concept, although in the California studies (*Anderson* and others, 1958) openings 1 to 2 tree heights in diameter were found to be better than smaller or larger ones.

Snow Interception

In addition to influencing the melting of snow by their absorption of solar radiation, coniferous forests intercept snow and so reduce the amount reaching the ground. To falling snow, the forest presents a three-dimensional and highly retentive screen. Flakes that are dry, small and wind-driven as well as those that are larger, wet and freefalling are captured by this screen, although perhaps not to the same extent. Depending on the nature of the snow and the storm amount, the intercepted snow may appear as a light, powdery deposit in the interstices of the foliage or as massive accumulations on all twigs and branches.

Interception alone does not mean less snow reaching the ground, since if that intercepted eventually falls as either snow or water there is no loss. Loss can only result from dissipation of the snow as vapor and this requires heat. Since the total heat supply to an area of landscape is not increased by the lodgment of snow on the canopy, it might be assumed that no loss is caused by interception. However, many measurements substantiate such a loss, and there is a physical basis for its existence.

Freshly fallen snow reflects up to 90 per cent of incident solar radiation and may have a temperature considerably below 0° C. A level surface of snow receives in winter a low level of radiation intensity. At noon on a clear day in January at 40° north latitude the direct solar radiation per unit area of a level surface is only about one-half of that on a surface normal to the sun. In a cold climate, these factors combined can mean that for weeks or months a level surface of snow will have little loss by sublimation and no loss by melt and evaporation. On the other hand, a surface steeply sloping to the south will show a comparatively high rate of ablation not only because of the higher rate of insolation but because of other factors associated with it.

Sublimation as well as evaporation of snow is proportional to the difference in vapor pressure between the snow surface and the ambient air. Moreover, vapor pressure is not linearly but exponentially related to temperature. Given two snow surfaces, one at -1° C and one at -7° C and an air dewpoint of -15° C, the rate of sublimation from the warmer surface will be more than twice as great as from the colder one. Such a 6 degree difference in surface temperature can easily exist between shaded and unshaded snow.

The melting of snow is associated with a definite threshold of energy supply. A high input of energy will cause melt while a lower one will not, no matter how long continued. Thus, on a surface normally exposed to the sun, melt may proceed during part of each winter day, but no melt at all occurs on slopes less favorably exposed. When snow melts, its albedo drops sharply, more radiation is absorbed, and melt is accelerated. The evaporation of water takes but 88 per cent as much heat as does the sublimation of ice, and at the melting point, the vapor pressure of a snow surface is at a maximum. Additionally, the melt water, if not evaporated immediately, serves to wet new foliage surface and increase the evaporating surface.

Snow intercepted and lodged in the forest canopy presents facets having all possible degrees and aspect of slope. Some of these are necessarily normal or nearly normal to the sun's rays at any given time and receive the maximum intensity of solar radiation. The heat from this direct radiation is augmented by radiated, convected, and conducted heat from the tree foliage with which it is in intimate contact and which is also in full sunlight. Even foliage covered by several centimeters of snow can be warmed by penetrating radiation and supply heat to the snow in contact with it.

On those facets where the heat intensity is sufficient to cause melt, the ablation is accelerated by a lowering of the albedo, an increase in vapor pressure and the fact that evaporation takes less heat than sublimation. When the heat intensity is insufficient to cause melt, sublimation is greater on the favorably exposed facets because of increased vapor pressures. The sum of all of these effects makes ablation an exponential function of heat intensity. Thus, the ablation from the many faceted surface of intercepted snow is greater than from a comparatively level surface such as that of the snow pack. Hence, intercepted snow is dissipated as vapor more rapidly than is snow that falls directly to the snow pack, and a deficit under the forest is caused.

Direct quantitative measurements on the vaporization of snow intercepted on a forest canopy would be difficult to obtain, and no data are known. A few pertinent and indicative observations on individual trees and branches have been made on the Fraser Experimental Forest in Colorado.

Data indicative of the amount of snow that a tree may intercept were obtained by supporting a severed tree on platform scales and reading the weight before and after each of a few storms. During one storm that produced 19 cm of snow, equivalent to slightly more than 1 cm of water, an Engelmann spruce (*Picea engelmannii* Parry) 4.5 meters tall intercepted more than 16 kg of snow. Although temperatures during and after the storm were well below 0° C, and consequently the snow was dry, snow adhered to the canopy so tenaciously that violent shaking to simulate a strong wind dislodged but one-third of the initial accumulation .

Weighing of a severed branch of lodgepole pine (*Pinus contorta* Dougl.) loaded with freshly fallen snow revealed the rate of vaporization that such snow may undergo. The branch was suspended from scales in full sunlight during a period when air temperature ranged from —7° to + 5° C, dewpoint was —14° C, and there was practically no wind. In 2 hours and 40 minutes the initial 227 grams of snow was reduced to 99 grams. There was no loss by melt and drip or by the falling of snow. All loss was by evaporation and sublimation; evaporation was probably more important. The snow in contact with and close to needles exposed to direct sunlight melted rapidly. However, the meltwater evaporated from the wet snow surface and from needles and twigs before it could collect into drops.

Cones of ice suspended over containers for meltwater collection were used to indicate the difference in heat supply between points within the canopy of a lodgepole pine and a point near the surface of the snowpack. During the mid-part of a clear winter day, with the cones in full sunlight, the ablation showed that the cone within the canopy received 50 per cent more heat than did a cone one meter beneath the crown and near the snow surface.

These results give minor support to the reasoning applied and to the general observation that less snow reaches the ground under a forest stand than in open areas. In western United States, measurements of the amount of snow reaching the ground universally show more snow in forest openings than in the adjacent forest. The observed seasonal excess has been as high as 27 per cent (*Kittredge*, 1953).

Several studies on the Fraser Experimental Forest in Colorado have been designed to reveal the effect of forest density on the loss of snow caused by interception. Partial cuttings in a mature, even-aged stand of lodgepole pine provided the means for testing the effects of several different densities. The original stand averaged 168 cubic meters per hectare in trees averaging 22 meters in height. Plots 3.2 hectares in size were established in the stand and were used to evaluate the effects on interception of residual stands having 168, 84, 56, 28, and zero cubic meters per hectare.

Precipitation on the site averages about 635 mm a year, of which about two-thirds falls as snow. The area lies at an elevation of 2,900 meters, with a north exposure. Snowmelt does not occur during late fall and winter months. Thus snowpack measurements in early spring reveal the total winter effect of interception on the snow accumulation. Precipitation gages were used to evaluate interception during the spring months. Measurements made on all plots during two years before any cutting was done enabled the

evaluation of differences among the plots associated with topographic and stand variations. After the timber was cut measurements of winter snow accumulation, spring snowfall, and summer rainfall were continued for 3 years. Measurements of soil moisture were also taken in order to evaluate the relation between stand density and the dissipation of soil moisture by evaporation and transpiration.

Comparisons among all the plots revealed a nearly linear and inverse relationship between the density of the stand and the snow reaching the ground. On the plots where no sawtimber remained, 29 per cent more snow was deposited than where the original stand of 168 cubic meters per hectare was left untouched. Intermediate depositions of snow were associated with intermediate stand densities. The data on snow, rain and soil moisture combined indicated that the increases in snow deposition accompanying the reductions in stand density would have been reflected in similar increases in streamflow if the stand changes had been applied over an entire watershed.

Two methods of thinning dense stands of second growth lodgepole pine were also tested for their effects on snow accumulation (*Goodell*, 1952). Before thinning, the stand about 6 meters in height, averaged 10,400 stems per hectare. Basal area was 20.5 sq meters per hectare. One thinning, uniform in nature, left an average of 1,550 trees per hectare, 2.6 meters apart; the basal area was reduced by 60 per cent or to 8.2 sq meters per hectare. The other thinning consisted of making an opening 5 meters in diameter about each of 250 trees per hectare, reducing the basal area to 10.5 sq meters per hectare. The uniform, heavier thinning caused an increase of 23 per cent in snow accumulation; the lighter thinning, an increase of 17 per cent.

The pattern of forest cutting seems to have little or no effect on the loss of snow through interception. This was the conclusion from the partial harvesting of a mature stand of Engelmann spruce and subalpine fir (*Abies lasiocarpa* (Hook.)) by three different patterns (*Love*, 1953). The patterns used were: uniform shelterwood, group selection, and alternate clear-cut strips. The same volume of timber was left under each pattern; namely, 95 cubic meters per hectare or 40 per cent of the initial volume. The openings created by the group selection harvest were 20 meters in diameter, somewhat less than the height of the residual stand. The clear-cut strips were of the same width and 160 meters long. These two patterns resulted in clearing half of the respective areas and removing half of the original timber volume. An additional 10 per cent was removed as a salvage cut from the residual stand. Measurements of the snow accumulations made before snowmelt began in spring showed that over a 3-year period, all patterns of cutting caused an average 22 per cent increase in snow accumulation, with no difference among the patterns.

It might be expected that on steep, north-facing slopes and others topographically shaded, the interception loss would be small because of the small heat supply. There is empirical evidence that this is not necessarily true; there is also a physical explanation. The experiment just referred to that resulted in a 22-per cent increase in snow accumulation was conducted on a 60 per cent north-facing slope. Sublimation and evaporation of the intercepted snow undoubtedly proceeds at a slower rate on such a slope than on one less shaded. This in itself allows the intercepted snow to remain longer on the trees and apparently permits the factor of time to compensate at least in part for the slower rate of loss.

Watershed experiments demonstrate more conclusively than can plot studies the effect of forest cutting on the flow of snow-fed streams. Two such

studies have been or are being carried on in western United States—both in the mountains of Colorado.

One experiment has been previously referred to by its location near the town of Wagon Wheel Gap (*Bates* and A. J. *Henry*, 1928). It was conducted on a site where annual snowfall averages 260 mm, one-half of the annual precipitation. For 8 years, water yield, snowfall, and several other climatic factors were compared on two forested watersheds. One watershed was then completely cleared of all trees more than one foot in height by cutting and subsequent burning, and the comparison continued for 7 more years. Comparisons between water yields from the two watersheds revealed an average annual increase attributable to the timber cutting of 2.5 cm of depth over the watershed area, or 16 per cent. The forest stand removed had very low density. In fact, only 23 per cent of the watershed area supported coniferous forest, the rest supported quaking aspen (*Populus tremuloides* Michx.) which because of its deciduous character can intercept little snow.

The other study is one being currently carried on at the Fraser Experimental Forest near Fraser, Colorado (*Goodell*, 1958). The site has many similarities in climate, topography, and soils to that of the earlier study. The chief differences are in the character of the vegetation and in the amount of snowfall. Before any timber was harvested, the Fraser watershed was 80 per cent covered with a dense mature stand of lodgepole pine, Engelmann spruce, and subalpine fir. Snowfall on the Fraser area averages about 500 mm per year.

The timber from the Fraser watershed has been partially cut in a pattern of alternate clearcut strips ranging in width from 20 to 120 meters, all orientated normal to the contours and thus heterogeneously with respect to sun and wind directions. The clear-cutting covered half of the 80 per cent of the watershed that supported mature, dense timber, or approximately 40 per cent of the total watershed area. The 20 per cent supporting a low density stand of immature trees was not disturbed.

The 3 years of record available since the timber harvest indicate that the timber removal has caused an average annual increase in water yield of 84 mm over the area, or 24 per cent. This increase is materially greater than that from the Wagon Wheel Gap study, as might be expected from the reduction in canopy density effected. At Wagon Wheel Gap, the reduction was around 23 per cent, since this was the total coverage by evergreen foliage. At Fraser the reduction was 40 per cent. Another relevant factor is the greater snowfall at Fraser.

It is doubtful that all of the increased yields from these two watersheds should be ascribed to the reduced snow loss associated with the reduction in the forest canopy. Some may properly be attributed to reduced transpiration of soil moisture.

Applications to Forest Management

Before using the presented evidence to draw conclusions as to how forests may be managed to control the regimen of snow-fed streams, we must specify the objectives desired. These will vary from place to place with the climate and the needs of the population. Where water supplies are deficient, the usual objective will be a dual one: to increase annual streamflow while causing the spring freshet to extend into late spring or early summer when needs for water are at their peak. Where water supplies are adequate, the

objective may be to ameliorate the hazard of spring floods caused by snowmelt.

The second objective appears the simpler. If, from a given watershed, we cause part of the snow to melt early and another part later, the flood-producing concentration of melt water in the stream will be lessened. By the amount that the yield from different parts of the watershed can be desynchronized, the flood will be ameliorated.

Topography does this task for us to a great extent. Snow on south-facing slopes characteristically melts earlier than snow on north slopes. Forest management can aid this desynchronization by increasing the variability of melt rates over a watershed. If, for example, the forest on a south-facing slope is managed to maintain wide, open strips running north and south, snow-melt should be seasonally early. If the opposite, north slope, is maintained in dense continuous forest cover, the melt should be comparatively late. Thus, melt water from the south slope should be largely discharged before the north slope yield reaches its maximum. Similar contrasts in management between east and west slopes should give similar results although here differences in time caused by topography are minor, and the major difference would be the result of the forest practice. Complexity arises with large watersheds when consideration must be given to the timing of discharges from numerous facets differing in degree of slope, aspect and elevation.

It is apparent that attainment of the first objective, that of increasing yields and also delaying them, is attended by basic difficulties. Snow accumulation is greatest under a forest of low density either uniformly so or containing many openings. On the other hand, melt is more rapid under such a forest than under one more dense with no unshaded openings. All evidence to date indicates that increases in yield obtained through reducing forest density are accompanied by more rapid melt and thus earlier streamflow. Until research may show how increased yields and delayed melt can be obtained simultaneously, compromise is necessary. This consists of maintaining the lowest level of forest density that will shade the snow surface during the seasonal and daily periods when melt rates are highest. It means taking into consideration the effects of topography on intensities of solar radiation and duration of shade, also the effect of tree heights.

Forest management for any purpose must take into account the silvical characteristics of the tree species comprising the forest. This is essential if the forest is to be maintained for the benefits to streamflow, for wood production, or for recreational opportunities. Generally speaking, tolerant species are best managed by the selective system, either single tree or group; intolerant species, by clear-cutting in strips or patches. Both tolerant and intolerant species are represented among the conifers of western United States. Thus the management of forests to benefit streamflow must, in some areas, use one system; in other areas, the other.

It seems probable that, where it can be applied, the selection system of management is the more favorable to realization of the objective of increasing water yield while retarding its discharge as streamflow. This system, whether single tree selection or group is better for avoiding the hot spots of unshaded forest openings than is clear-cutting with its larger openings. Topographic consideration should influence the density at which the stand is maintained. On slopes topographically shaded the density can be less or openings larger, with a gain in snow accumulation. On more exposed slopes the density should be maintained at a higher level or openings smaller to minimize melt rates.

Where clear-cutting by strips or patches must be used, the openings should be kept as small as is consistent with the regeneration requirements of the species and should be oriented so shade is at a maximum during the periods of most intense radiation. Investigators in California (*Anderson* and others, 1958) have tentatively concluded that on south slopes, strips should run northwest and southeast; on north slopes and level areas, east and west. On east slopes they suggest L-shaped openings with the arms extending north and west; on west slopes similarly shaped openings, but with the arms extending north and east. They conclude that the strips should be 1 to 2 tree heights across, since on June 1 more snow was found in such openings than in either larger or smaller openings. They also specify that during a cutting cycle the cutting should proceed from north to south so as to always maintain a shading barrier of mature trees to the south.

On areas exposed to strong winds, it may be that clearings can be designed to take advantage of this fact and prolong snowmelt. Strips may be oriented so that winds will cause the drifting of snow from the cleared strips into adjacent timber where it is shaded from solar radiation. Funnel-shaped strips might do this best. Strips may also be designed to encourage the drifting of snow from south-facing slopes to slopes of different aspect where topographic shading exists.

Under both the selection and the clear-cutting systems, intensive management can be expected to yield the greatest benefits to streamflow. This means early and periodic thinnings to maintain moderate density in young as well as older stands. A short cutting cycle is desirable. How short it should be cannot be stated yet. If large areas are cleared at long intervals, strong cyclic fluctuations in annual water yield can be expected. A similar average benefit in yield and smaller periodic fluctuations should result from more frequent cuttings of smaller areas.

Such tentative and general conclusions are all that can be drawn now to guide forest management in western United States toward increased water yields and better stream regimen. More specific guide lines must await further research.

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INCREASING WATER YIELDS BY CUTTING FOREST VEGETATION

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ABSTRACT

Forest cutting to reduce evapotranspiration loss has its advocates during water shortages. But underlying such proposals is little research to guide prescriptions or enable predictions of response. Controlled experiments at the Coweeta Hydrologic Laboratory, North Carolina, show large streamflow increments from clear cutting mountain hardwood forests on two small watersheds, first-year increases being 15 and 17 area inches, all as regulated base flows. The yearly increase levelled off at 11 inches after the 3rd year where all regrowth was cut back annually; but it declined progressively on the other unit where a young coppice forest grew back. Cutting a shrub-understory increased annual yield about 2 inches. Other experiments are measuring water yield response from stand density reduction, cutting cove hardwoods, and converting the native forest to pine and other cover types. Learning how to favorably influence water yields for specific situations will require much more basic research, particularly study of water use requirements of forest trees and of the related plant-soil-climatic factors governing the evapotranspiration process.

RÉSUMÉ

La coupe des bois en vue de réduire l'évapotranspiration trouve en période de sécheresse un certain nombre de disciples. Il existe cependant peu de travaux à ce sujet qui pourraient servir de base et fournir quelques indications quant aux résultats à obtenir. Des expériences contrôlées effectuées au Laboratorie Hydrologique de Coweeta en Caroline du Nord indiquent que dès la première année un accroissement important du courant d'entrée de deux bassins de l'ordre de 15 à 17 pouces à débit régulier est produit par la coupe d'éclaircissement de bois durs en forêt de montagnes. Après la troisième année cet accroissement s'arrête à environ 11 pouces sur les terrains recoupés chaque année, mais s'efface progressivement où l'on a laissé grandir le taillis. La coupe d'arbustes produit un accroissement d'environ 2 pouces. L'accroissement du débit des eaux par éclaircie, coupe d'arbres à bois dur et implantation de pins et autre végétation en remplacement des essences indigènes fait l'objet d'autres recherches. Pour apprendre comment influencer favorablement le débit des eaux pour chaque cas particulier il faudrait davantage de recherches élémentaires, notamment en ce qui concerne les besoins utiles en eau d'arbres forestiers et des facteurs relatifs végétation-sol-climat qui contrôlent le processus d'évapotranspiration.

Forest vegetation, much valued as watershed cover, levies heavy toll on water supplies as the price for keeping soils stable and in optimum condition for water intake and storage. And critical water shortages in the United States, as elsewhere, are prompting proposals to cut forests to obtain greater water yields. An example in the arid Southwest is the large-scale program under way for modifying forest-range vegetation in the Salt River Watershed in Arizona (Barr, et al., 1956). As yet, there is little real research knowledge anywhere to guide cutting prescriptions or from which to postulate probable response. As one contribution, this paper presents results from studies at the Coweeta Hydrologic Laboratory in western North Carolina—the first con-

trolled watershed experiments, it is thought, which show conclusively that water yields were substantially increased by forest cutting without producing attendant increases in stormflow or soil loss.

In the United States, a growing body of research results have documented unfavorable effects of deforestation with respect to soil impairment, sediment production, and the quantity and timing of stormflows. But controlled experiments have produced little evidence that watershed treatment induces much if any change in total water yield. This is not surprising, since there are few such studies, and complex processes and measurement problems are involved.

Two studies in Colorado—the classical Wagon Wheel Gap experiment (Bates and Henry, 1928) and a more recent preliminary study (Goodell, 1958)—report increases in snow-fed streams, chiefly as spring freshets, from cutting high-elevation timber stands. But other findings in the humid eastern United States indicate little if any change in total water yield some 15 and 19 years, respectively, after two critically eroded watersheds were completely reforested (Tennessee Valley Authority, 1951, 1955). Thus Coweeta results have unique, early value in indicating some treatment possibilities and for guiding much-needed work in this neglected phase of water management research.

The Coweeta Watershed Studies

The Coweeta Hydrologic Laboratory is a 5600-acre outdoor installation of the U. S. Forest Service where research has been under way since 1934 to develop principles of managing forest lands for water production and control. The Laboratory is in an 80-inch high rainfall belt of the Southern Appalachian Mountains; and its many small drainage catchments, from 25 to 200 acres each, occupy a rugged terrain of steep slopes and narrow ridges lying at elevations of 2200-5200 feet. Soils, chiefly weathered schists and gneisses, are relatively deep and porous and overlie rather tight bedrock. A dense, secondgrowth, deciduous hardwood forest supporting a rich flora of understory plants is dominant with scattered pines on the drier ridges. There has been no logging or other disturbance since about 1923.

In earlier years Coweeta research pioneered in studies of timing and delivery of flows from undisturbed forest; and later in measuring streamflow response when forest land is badly used. The program is now largely geared to study of water yield processes, the factors affecting them, and how they may be modified by watershed management. Basic instrumentation at Coweeta has been precipitation-streamflow measurements prior to and following treatment of small unit watersheds, with treatment response gauged through changes in flow, using an undisturbed watershed as a permanent control. By calibrating test-unit performance against that of the control, reliable estimates of altered flow due to treatment can be made, and variations due to climate and other extraneous factors greatly minimized.

Two well-known, classical experiments at Coweeta afford conclusive evidence that cutting all forest vegetation can produce very substantial increases in water, delivered as usable, regulated flows. A third study, in which the shrub understory was cut, gave similar, though lesser, water-yield response. This paper, in the main, interprets results from these three key investigations; and discusses some indicated needs which prompt additional studies.

Watershed 17, a 33-acre, north-facing unit, was cut over in 1941 after a 5-year calibration period to measure maximum streamflow response when

all woody vegetation was cut (Fig. 1). (Preliminary results were reported by Hoover, 1944). Logs and slashings were left in place and no wood products removed; and subsequently all sprouts and invading growth were cut back each year except in three war years, 1943-1945.

Watershed 13, a nearby 40-acre catchment, was similarly clear-cut in 1939-40 after calibrating performance for 3 years; but a young coppice forest was allowed to grow back (Kovner, 1956). The original cover, as on Watershed 17, was predominantly oak-hickory forest with basal area averaging 111 square feet per acre. By leaving lopped material in place, soil disturbance was kept to a minimum; and a dense tree sprout cover took over the first year after cutting.

Watershed 19, a 70-acre tract, was treated in 1948-49 by cutting the dense understory of mountain-laurel (*Kalmia latifolia* L.) and rhododendron (*R. Maximum* L.) (Johnson and Kovner, 1956). This widely-prevalent, evergreen cover averaged about 10 feet in height and accounted for some 20 percent of total woody basal area on the unit. Some stems were 85-100 years old and up to 9 inches d.b.h.

Comparative increases in annual vield—Large increments in streamflow were produced in each instance by clear cutting Watersheds 17 and 13, the increases totalling 17 and 15 area inches respectively the first year (Fig. 2). These represent *measured* over *predicted* flows by regression analyses, and are for the Coweeta water year, May 1-April 30. They came largely as regulated base flows without measurable changes in peak discharge, stormflow, or turbidity; as before treatment, less than 10 percent of total water yield was storm discharge, none of which reached streams as overland flow.

On Watershed 17, the annual increases declined to about 11 area inches after the third year and were maintained at that level for the rest of the period. This was response to partial re-establishment of water-demanding plant cover due to lush growth of sprouts and invading woody plants which sprang up the first year and have grown back each year to heights of 5-8 feet after cutting. Observations show no significant changes in soil properties, though surface accumulations of litter are somwhat less than those on the forested control. Thus Watershed 17, though clear cut repeatedly, remains essentially in top hydrologic condition with a forest soil channeled by vigorous root growth and receiving yearly renewal of litter from leaf fall and sprout-cutting operations. In no sense does it resemble a logged, denuded area.

On Watershed 13, cut in a similar manner but with forest regrowth permitted, water yield increases, similarly large at first, have declined with re-establishment of a vigorous, young coppice forest. But it will be noted that the increase was still a substantial 5 inches the 13th year after cutting, at which time basal area of the new stand was 52 sq. feet per acre—about half that of the original forest. Apparently, increases will be negligible after the 35th year and should return to pretreatment levels in about the 50th year.

This particular experiment is of key significance not only in demonstrating that well regulated increases in streamflow were produced by cover manipulation but also that they are progressively responsive to growth increments of the vegetation. Moreover, it affords impressive evidence of a substantial streamflow response long after one cutting operation, a response which will extend through much of a timber rotation.

Cutting the dense shrub understory on Watershed 19 produced a streamflow increase of 2.8 inches the first year, and yearly increases averaging about 2.0 inches for the 6 post-treatment years. Again there was no obser-

Fig. 1 — (Upper). General view of the Coweeta area; and of Watershed 13 soon after cu with a young coppice forest getting established. (Lower). Watershed 17, similarly with logs and slashings left and regrowth cut back annually.

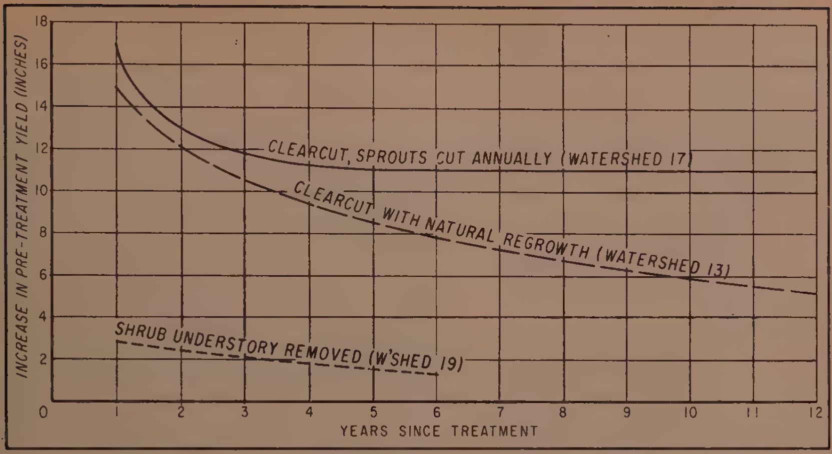

Fig. 2 — Comparative streamflow increases from forest cutting

vable change in proportion of flow contributed by stormwater. Although the increases seem small, it should be noted that cutting the shrubs—about 20 percent of total basal area—gave added flow somewhat proportional to the 11 area inches obtained by cutting everything on Watershed 17.

Obviously, the greater water yields obtained in these test cuttings are response to lessened transpiration draft. Under conditions of treatment, with slash continuing to have an insulating effect, evaporation loss from the forest floor probably has changed very little; and the interception losses, though doubtless reduced, have not been eliminated.

Indicative of this relationship is evidence (Kovner, 1956) of close correlation between measured water yield increases and annual water losses as calculated from the water balance equation: Evatranspiration = Precipitation — Streamflow ± Storage changes (difference in groundwater storage at beginning and end of year) (Table 1). Thus when calculated evapotrans-

TABLE 1 — *Streamflow increases compared with reduced evapotranspiration loss, Watershed 13*

Year since cutting	Flow increase (regression analysis)	Reduced water loss (water balance equation)
	Inches	*Inches*
1	14.45	18.33
4	9.76	10.34
8	7.30	7.31
12	5.78	5.63
13	4.99	4.08
13-yr. mean	8.14	8.20

piration loss for a given year is deducted from the average pretreatment loss (38 inches), the value obtained (Col. 3) approximates the increased water yield as measured for that year. These reciprocal values—flow increase and reduced water loss—when averaged for the 13 years of record are in remarkably close agreement.

One important contribution of these studies is the gross measures they afford of how much water a well-supplied, mesophytic, high forest may use. In all probability, the transpiration draft exceeds the first-year 17- and 15-inch flow increases reported herein, since it is evident total transpiration was interrupted only briefly the first summer while tree sprouts were beginning to grow back. Nevertheless, these approximations, obtained from natural drainage units supporting well-watered forest cover, afford important bench-mark values in water balance and evapotranspiration research.

Seasonal distribution of increases—Monthly distribution of streamflow increases after cutting Watersheds 13 and 17 reflects the hydrology of Coweeta watersheds and suggests some water-yielding, treatment possibilities as well.

Figure 3 shows for Watershed 17 the mean increases in monthly water yield after cutting, based on 15 years of record. There are appreciable streamflow increases for every month, including those of the spring-summer period when evapotranspiration draft is greatest and considerably exceeds rainfall accretion.

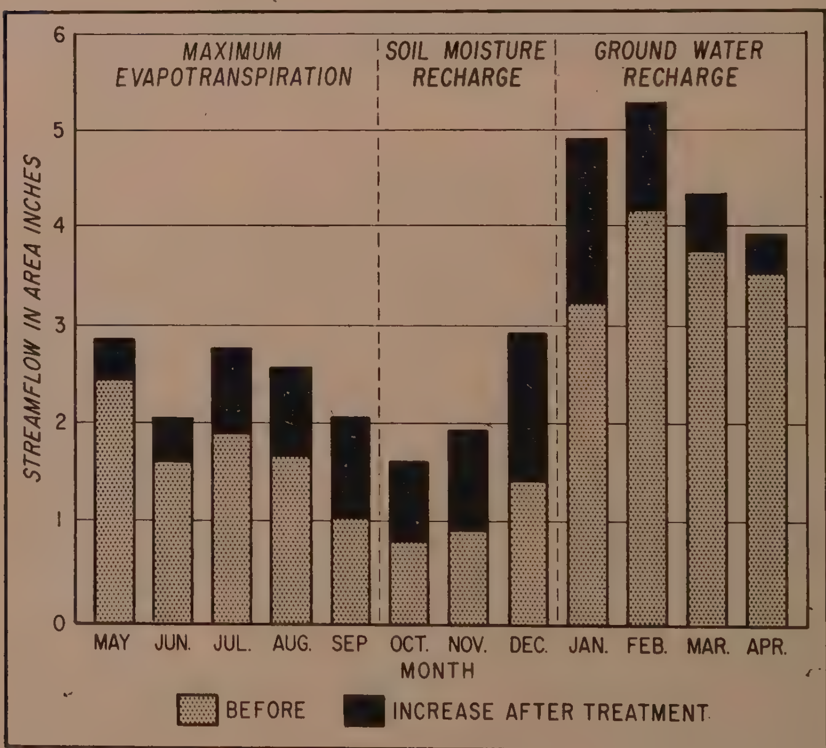

Fig. 3 — Mean monthly streamflow increases after cutting, Watershed 17.

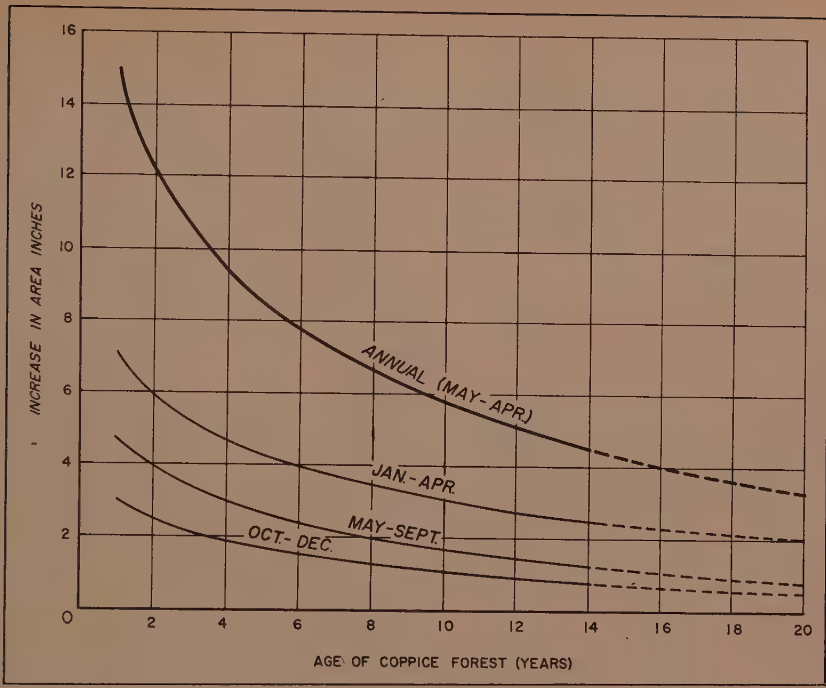

Fig. 4 — Water yield increases by seasons while a coppice forest re-established itself.

Percentage-wise the increases are greatest (exceeding 90 percent) in fall months, September-December, when streamflow normally is lowest and water shortages most acute. But quantitatively, the biggest increases are in the dormant season, December-April, also the period of groundwater recharge. Surprisingly, more than half the total increase, approximating 11 inches annually from this watershed, comes in the winter, when evapotranspiration as such can be little influenced by forest cutting. Obviously, there is a pronounced seasonal lag relationship operating here through soil reservoir storage.

Trends in seasonal water yields from Watershed 13, where a coppice forest grew back, are shown in Figure 4. As for Watershed 17, the greater increases were in the dormant period.

Seasonal distribution of the increases can be rationalized in part by considering Coweeta water cycle relationships. Mid-April, when trees leaf out and watersheds have been fully recharged, ushers in a 6-month water deficit period of maximum evapotranspiration. Streamflow recedes steadily with the declining water tables and is recharged only by the occasional larger storms of spring and summer; and with less-demanding watershed cover (hence a somewhat lower soil moisture deficit) these few storms may produce some streamflow increase during growing-season months.

Beginning with October rains, this trend is reversed, though streamflow may continue to drop during autumn months. Frosts remove foliage, and

water losses to the atmosphere decline with this and cooler weather. Soil moisture build-up proceeds rapidly and by December the soil mantle usually is at "field capacity"; and during the ensuing winter recharge period, streamflow responds promptly and directly to rainfall accretion. Thus, inferentially, a watershed cover of lesser water demand must make cumulative contributions during summer months toward a build-up in soil moisture and water tables which carries over to and pays off in greater streamflow months later during the groundwater recharge period, December to April.

Other water yield studies—Watershed treatment experiments afford only a gross measure of net treatment response in terms of streamflow and have other definite limitations, also. But since little is known about water use by forest stands, other Coweeta unit watersheds are being utilized in cover-alteration pilot tests to guide more basic research. Stand density-water yield relationships are getting special attention in tests to gauge immediate response from partial cuts or tree-eliminating treatments. In 1955, half the basal area on an 88-acre watershed was deadened by chemical basal spraying; and other reductions in basal area are planned on companion units. The preliminary indication is that the first-year increase in water yield was somewhat less than half that measured the first year on Watersheds 17 and 13.

Other possibilities have been explored, notably cutting the more valuable cove hardwoods. This type occupies the deeper, better-watered, more productive soils—the areas most likely to sustain base flows and hence produce greater water yields when in forest cover of lesser water demand. Early results are inconclusive but suggest no particular advantage in cutting this type.

Another major Coweeta study, started in 1955, compares water yield responses from a series of 5 calibrated watersheds averaging about 30 acres and representing: (1) native hardwood forest (control); (2) white pine (*P. strobus* L.) planted on north and on south-facing watersheds, respectively; (3) perennial grass; and (4) a low shrub cover. This is a long-term pilot study in type conversion to measure differential water yield responses from natural drainage units; and to afford suitable locale for supporting studies of soil-site change, plant rooting habits, seasonal use of water, and other aspects affecting water gains and losses. Among developments prompting the latter study are large-scale pine planting programs in the region, and the questions these pose whather shifting hardwood sites to pine may unfavorably affect soil and water relations.

Some Indicated Needs

Whether forest cutting or other manipulation of cover can produce more water for specific situations of terrain, soil, and climate must remain largely outside the realm of accurate prediction at this stage. Use of natural drainages, as at Coweeta, to test cover alteration-streamflow response is a highly useful approach; but unfortunately it can afford only partial answers. And much of the knowledge to enable reliable prediction of yield must be sought in more basic studies of cover-soil-climatic relationships and how these operate or can be modified to influence hydrologic processes.

Essentially, this means study of water use requirements of forest stands and of factors governing evapotranspiration losses. Hence, the future Coweeta program calls for much study of the plant itself, its moisture requirements, and regulating mechanisms; of climatic factors such as solar radiation, temperature, and wind as modified by plant cover; of condensation, interception,

TABLE 2 — *Streamflow increase with a developing coppice forest, Watershed 13*

Time	Stand attributes		Stream increase over prior yield
	Basal area per acre	Annual foliage produced per acre (1)	
	Sq.ft.	*Tons*	*Area inches*
Pretreatment	111	1453	—
1st year after cut	0	0	15
13th year	52	1412	5
40th year (est.)	100	1453	0

(1) From sampling leaf fall (oven-dry weight) on Watershed 13 and its control.

and other water cycle components; and of the basic hydrology of small watersheds as altered by, or independent of, vegetation influence.

Coweeta observations lend special emphasis to some of these needs. Streamflow increase associated with changes in the coppice stand which re-established itself on Watershed 13 is a case in point (Table 2).

Here a high forest with trees of many sizes was replaced by a vigorous even-aged, coppice stand of somewhat altered species composition, which, in the 13th year, when dominant trees were more than 30 feet high, was using about 5 inches less water than before. Total basal area by that time was about half that of the original stand, but on about twice as many stems. But total crown density (the transpiring potential) as indicated by foliage production measurements was not significantly less than for the original old-growth forest. The explanations of lessened water demand may lie in part in differences in stand structure or rooting habits or the altered microclimate; but it is a logical inference that the needs and internal water relations of the developing young forest itself hold some of the answers.

Greatly needed in any assessment of consumptive demands of forest trees is an understanding of their physiological processes and how they actually use water. Evidence of this is the changing water demands of certain cultivated plants, seasonally or at different stages of development, whatever the favorable factors of temperature, soil, and water supply. In one approach to this much-neglected field of research, an exploratory study is under way at Coweeta of soil-tree-atmospheric moisture tension relations. This focuses on development of techniques for measurement of diffusion pressure deficit ("suction tension") in tree foliage as a possible indicator of water use and operating as a water-regulating mechanism in plants.

Equally important in attempts to control evapotranspiration loss through forest cutting is knowledge of how such cutting modifies solar radiation, and other important variables. There are strong indications from preliminary analysis that south-facing watersheds at Coweeta, receiving about the same rainfall as north-facing Watersheds 13 and 17, may yield much less water after cutting. Preliminary work is under way at Coweeta to study slope-aspect relationships affecting solar radiation and other key

meteorological factors; and much additional research will be needed to assess the many microclimatic effects of forest cutting.

A related need in water yield prediction is research to improve empirical formulae and techniques for estimating evapotranspiration from climatic variables or by energy-budget and other procedures. Coweeta, with an elevational range in evapotranspiration of about 40 to 20 inches annually and a combination of climate, soils, and forest cover which apparently maintains atmospheric water losses at or near "potential" values, affords unique opportunity for this. Not the least of the advantages are the measurement standards afforded of total evapotranspiration loss from natural watershed units as approximated in the Watershed 17 experiment.

This paper, in reporting evidence from some 20 years or more of controlled experimentation at Coweeta, affords some values which may approach the upper limits of regulated, water-yield increase where soils are known to be deep and porous, the climate humid, and the cutting treatment drastic. But perhaps it serves best to point up difficulties and some research needs in working toward development of reliable prediction methods to guide cutting prescriptions. Quantitative yield values, though precisely developed for small experimental watersheds, are not directly transposable as such to other areas; nor will large-scale cutting operations of a trial-and-error nature afford many answers. It will take a great deal more fundamental research to understand the nature and mechanics of water disposal processes on forest lands. Moreover, these studies are needed soon if we are to exploit the water-yielding possibilities of forest cutting or avoid ill-founded attempts to get more water in this manner.

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PREDICTION OF SOIL MOISTURE FROM SOIL AND WEATHER RECORDS

by HUBERT D. BURKE (1) AND WILLARD J. TURNBULL (2)

SUMMARY

As part of a study to develop means of estimating the ability of soils to permit vehicular traffic, a method was developed for predicting the moisture content of soils. Data used in development of the method were obtained from daily soil moisture and weather records kept for periods of one to two years at 131 sites throughout the United States. Chief influences on moisture accretion in the surface foot of soil were found to be the amount of rainfall and the amount of space available in the soil for water storage. Moisture depletion rates varied with the moisture content of the soil but followed characteristic curves for each season.

The prediction method was tested on more than 600 sites throughout the United States. Results indicate that this empirical method can be used to predict soil-moisture content of sites for which the following are known: accretion and depletion characteristics, minimum size storm that will add moisture to the soil, field maximum and minimum moisture contents, and amount of rainfall during the period covered by the prediction. For well-drained sites, the prediction error was less than 0.3 inch of water per 6 inches of soil.

RÉSUMÉ

On a développé une méthode pour prédire l'humidité du sol dans 131 zones réparties sur les États-Unis dont les sols étaient complètement différents l'un de l'autre et dont on a noté les observations journalières. On a trouvé que les accroissements de l'humidité du sol causés par les pluies dépendent de l'importance des tempêtes et de l'emmagasinage disponible. On a tracé les courbes de l'accroissement de l'humidité en tenant compte de ces deux conditions. Dans ces 131 zones, on a déterminé l'épuisement saisonnier de l'humidité du sol et on l'a exprimé par une série de courbes indiquant le teneur en eau en fonction dut temps. A partir de ces relations on a calculé une série de moyennes et ont les a utilisé, avec les données sur les valeurs maximum et minimum de l'humidité du sol dans ces zones, pour faire des prédictions d'essai de l'humidité du sol dans des zones où l'on disposait seulement d'une information générale sur le sol en plus des enregistrements de la précipitation.

Ces prédictions d'essai ont été faites sur plus de 600 zones réparties sur les États-Unis, y compris Alaska et Puerto Rico. Les résultats ont montré que cette méthode empirique, qui est basée sur les zones ayant des données suffisantes pour déterminer le régime de l'humidité du sol, pourrait être appliquée avec succès pour prédire le teneur en eau du sol. Pour les zones bien drainées, l'erreur était moins de 0,3 pouce (7,62 mm) d'eau les 6 pouces (152 mm) de sol. La méthode n'a pas été élaborée suffisamment pour les zones ayant une nappe aquifère élevée.

INTRODUCTION

In studies of soil strength in relation to the movement of vehicles, the Corps of Engineers, U. S. Army, has demonstrated that bearing strength varies with moisture content and with the nature, arrangement, and size

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distribution of the soil particles. These findings suggested that trafficability of the soil for vehicular movement might be estimated if the water content could be predicted. A cooperative effort of the U. S. Army Engineer Waterways Experiment Station and the Vicksburg Research Center of the U. S. Forest Service has been devoted to this end.

This paper summarizes the relations found necessary for the prediction of moisture in the surface foot of soil and discusses the accuracy with which these predictions have been made.

The Development of Soil-Moisture Prediction Relations

Prediction requires knowledge of two principal processes, accretion or net gain in soil moisture, and depletion or net loss. In this study these processes were considered only in reference to the 0- to 6-inch and 6- to 12-inch layers, the two layers of soil of greatest significance to trafficability. For each of 131 sites throughout the United States the daily march of soil moisture was plotted for each of these two layers. Rainfall was graphed on the same sheet (fig. 1). Accretion and depletion relations were developed empirically from this soil-moisture and rainfall record. Variation in soil, vegetation, topography, and climate caused these relations to differ between sites.

Accretion

Accretion was found to depend chiefly on the amount of rainfall and the available pore space in the soil. When the rainfall was greater than the pore space, accretion was directly related to pore space; when the rainfall was less than the pore space, accretion was directly related to rainfall. The various factors that influence accretion, such as intensity and duration of rainfall, runoff or run-on of surface water, interception of precipitation by vegetation and ground-surface litter, the effects of topography, and the structure, texture, and organic content of the soil, are incorporated, at least in part, in the accretion relations.

Very small storms are wholly intercepted by vegetation and ground cover and do not contribute to accretion. The minimum-size storm considered in the prediction method was the smallest for which, on the average, moisture gain was canceled by moisture loss, resulting in no net change of moisture content for the 24 hours in which the storm occurred.

Tests of the accretion relations led to the formulation of two classes:

I: Total rainfall less than the available storage space in the 0- to 12-inch layer.

II: Total rainfall equal to or greater than the available storage space in the 0- to 12-inch layer.

Moisture accretion was determined for a particular soil layer by subtracting the moisture content before the storm from the content soon after the storm. Accretion was determined for each storm at each site studied. The field maximum moisture content for each layer was obtained by selecting the recurring peak values from soil-moisture records. Available storage was then determined by subtracting the actual moisture content before the rain from the field maximum.

Class I accretion relations were derived by computing the regressions of rainfall against accretion. Typical regressions were $Y = 0.46X - 0.01$ for

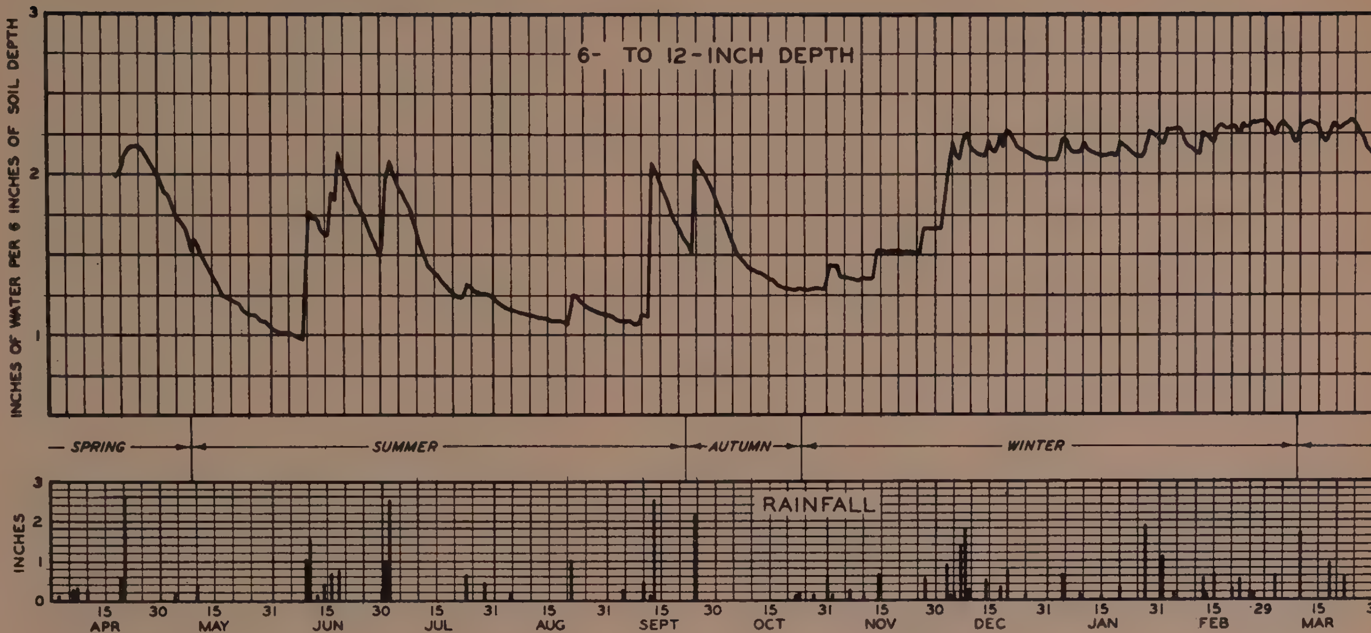

Fig. 1. Daily soil-moisture record and concurrent rainfall for Commerce silty clay at Mound, Louisana, 1951—1952.

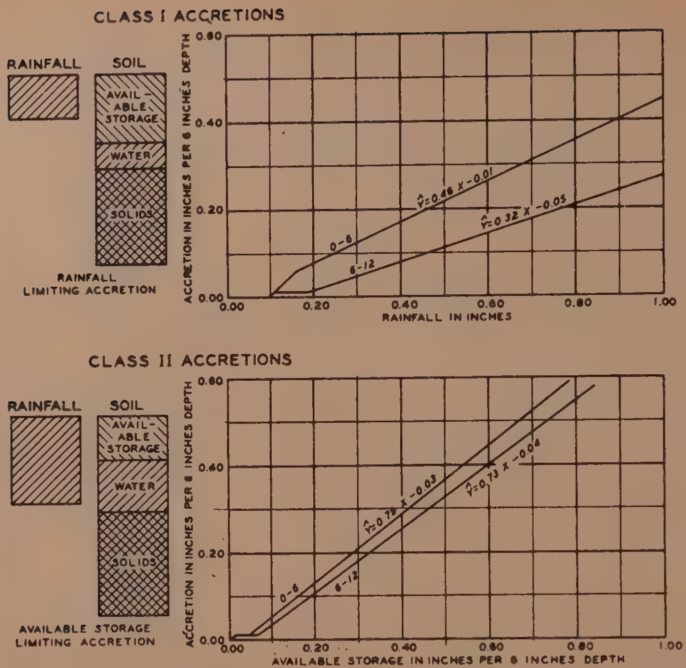

Fig. 2. Typical regressions for Class I and Class II accretions in Commerce silty clay.

the 0- to 6-inch layer, and Y = 0.32X — 0.05 for the 6- to 12-inch layer. Here X is rainfall in inches and Y is accretion of soil moisture in inches of water per 6 inches depth of soil (fig. 2). The regression line for Class I accretion was drawn from zero accretion to a point corresponding to the minimum storm—usually 0.1 inch.

For Class II accretions a typical regression was Y = 0.79X — 0.03 for the 0- to 6-inch layer, and Y = 0.73X — 0.04 for the 6- to 12-inch layer. Here X is available storage in the soil expressed in inches of water per 6 inches depth of soil, and Y again is accretion of soil moisture. For the Class II accretions, the regression line was adjusted to zero available storage.

As season had little effect upon accretion curves, Classes I and II accretions were derived from, and applied to, an annual record.

Because the study was concerned with the retention of water in the surface foot of soil only, the amount lost by surface runoff and by percolation through the surface foot was not pertinent. Little or no runoff occurred with Class I accretions except on bare areas. With Class II accretions available storage was the limiting factor and it was immaterial whether the excess rainfall ran off or percolated through the surface foot. Some sites, in depressions or at the base of a slope, had more accretion than rainfall; here consistent run-on shifted the slope of the regression line.

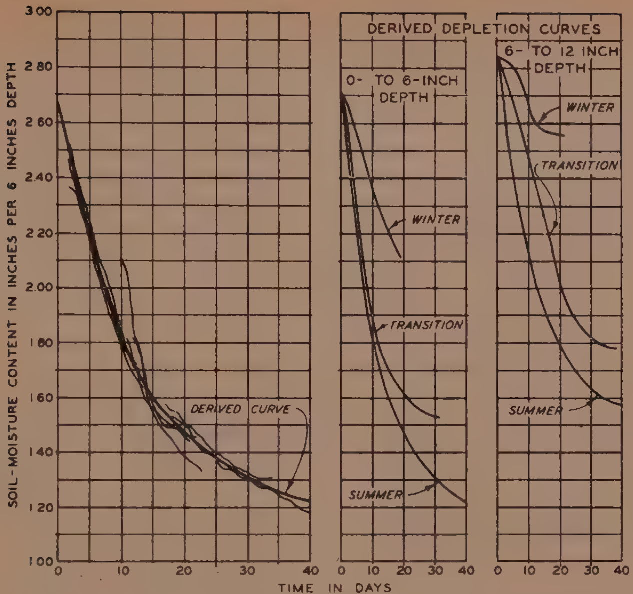

Fig. 3. Left: Derivation of a typical depletion curve from a family of 8 actual summer depletion curves;
Right: Seasonal depletion curves, Commerce silty clay.

Depletion

Depletion curves were derived for the 0- to 6-inch and 6- to 12-inch layers from the interrain portions of the graph of soil moisture. These graphs indicated that depletion varied seasonally; summer rates were much greater than winter rates, and spring and autumn rates about intermediate.

When the depletion segments of the soil-moisture records were traced for each season, it was found that a smooth line through the family of segments could be used to represent the depletion curve for each season. Spring and autumn curves were sufficiently similar to permit the use of an average curve. A typical composite curve and a set of seasonal depletion curves are illustrated in fig. 3.

Depletion relations could not be developed for some sites that had a narrow range of measured moisture content. Poorly drained soils, such as peat sites in Wisconsin, did not dry sufficiently to reach field minimum. On the other hand, at arid sites, as in New Mexico and Colorado, the soil did not become wet enough to reach the field maximum. Values at the wet end of the curve were not observed and only fragments of the depletion curve could be drawn. However, inasmuch as these soils are only occasionally wetted to field maximum, prediction of soil moisture can be made satisfactorily from these fragments as long as conditions wetter than those recorded do not occur.

The rate of moisture loss at the dry end of the curve was determined in some cases by extrapolation. A laboratory-determined value equal to wilting

point (15-atmosphere tension), when available, was used as a guide in extending the daily rate of loss to zero. When moisture content approaches the wilting point, approximately 2, 5, and 10 days are required to remove 0.01 inch of water from each layer during the summer, spring-autumn, and winter seasons, respectively.

Soil-moisture records of the 6- to 12-inch layer were analyzed to determine the dates on which a shift was to be made from one depletion curve to that of the next season. Starting dates for the autumn and winter curves were especially difficult to fix because the moisture content in many locations was at a nearly constant field minimum. Observations of coloration and fall of leaves and seasonal changes in air temperature were used as partial guides in selection of these transition dates.

Field-maximum and field-minimum moisture contents

The field-maximum moisture content establishes the wet end of a depletion curve, and is used in calculating storage space. Since the field-maximum values for a given soil layer were obtained by selecting the recurring peak values from daily soil-moisture records, records for one full year usually were needed to obtain sound values. In arid regions or during drought cycles, longer records may be necessary.

The field-minimum moisture content corresponds approximately to the wilting point. In some cases, particularly in the surface layer of clay soils, evaporation may reduce it below the wilting point.

The Soil-Moisture Prediction Method

As developed so far, the prediction method applies to areas where rainfall is the chief or only accretion source.

Prediction for such areas requires data for the six factors just discussed: (1) field-maximum moisture content, (2) field-minimum moisture content, (3) smallest storm that appreciably wets the soil, (4) soil-moisture accretion curves, (5) seasonal soil-moisture depletion curves, and (6) dates of change between different rates of soil drying.

Prediction is made by a bookkeeping procedure that begins with a known or assumed moisture content. Weather records can be used to estimate the most recent occurrence of field maximum or wilting point for use as the starting point.

For each drying day the amount of moisture lost, as indicated by the appropriate seasonal depletion curve, is subtracted; for days with more than the minimum storm, the amount of moisture gained is obtained from the accretion curves and added. This process of adding and subtracting continues until the soil-moisture content for the desired day is predicted. This method is used both with specific site data and with average relations.

Average relations were developed to permit prediction without prior contact with the soil. Information was collected on 131 sites at 22 locations throughout the United States, but all sites did not contribute to the derivation of all relations. Data for average accretion relations were drawn from 75 sites, for depletion relations from 48, for minimum storm size from 89, for maximum moisture from 39, and for minimum moisture from 59. Dates marking change in season were determined from the record at the 22 locations.

The applicability and reliability of these average relations were tested over a wide range of conditions by making predictions for a period of about

one year on 625 sites (3). These consisted of 24 of the sites previously used for development of the method and 601 survey sites established for this test.

Differences between predicted and measured moisture content were used as a check on accuracy. Between 20 and 115 comparisons were made for each prediction development site and from 4 to 7 comparisons for each survey site. The individual differences for each site were averaged, regardless of sign, to determine the deviation for that site.

For the 24 prediction development sites, predictions were first made using rainfall data taken at the site and specific accretion and depletion relations derived for that site. Deviations of predicted from measured moisture content were obtained and averaged for all sites by soil layers. For the 0- to 6-inch layer, the average deviation for all predictions from these specific site data was 0.13 inch of water for the 0- to 6-inch layer and 0.09 inch for the 6- to 12-inch layer.

The average prediction relations were then applied to these 24 sites and again deviations from measured moisture content were obtained. These deviations were somewhat larger than with the specific relations, averaging 0.26 inch for the 0- to 6-inch layer and 0.23 for the 6- to 12-inch layer. (At a bulk density of 1.33, 0.08 inch of water per 6 inches of soil is equivalent to about 1 per cent water by weight.)

Next, predictions for the 601 survey sites were made from the average soil-moisture prediction relations. The average deviations of the predicted from actual moisture contents were:

Regions of United States	Site No.	Surface to 6-inch Depth Inch	6- to 12-inch Depth Inch
Southern	178	0.28	0.28
Northeastern	122	0.37	0.37
Lake States	160	0.38	0.33
Intermountain	141	0.32	0.28
All survey sites	601	0.33	0.31

In this test, the deviation between predicted and measured soil-moisture values was greater than in the other trials. This loss in accuracy may be ascribed to use of rainfall records secured from the weather station nearest the site, rather than from gages at the site itself. Some of the inaccuracy was undoubtedly also caused by use of average rather than specific prediction relations.

It may be concluded that this method for predicting soil-moisture content, developed from sites with sufficient data to define the soil-moisture regime, can be applied to other sites, for which these data are not available, with an accuracy of 0.32 inch of water per 6-inch soil layer which is approximately equivalent to 4 per cent moisture by weight.

(3) U. S. Forest Service — U. S. Army Engineer Waterways Experiment Station, *Forecasting Trafficability of Soils; Report No. 5, Development and Testing of Some Average Relations for Predicting Soil Moisture.* Waterways Experiment Station Technical Memorandum 3—331, 1959.

THE PROBLEM OF PHREATOPHYTES

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SUMMARY

Phreatophytes occupy large areas along the streams and rivers and on the flood plains of the Southwest. These plants consume water that could be put to better use. Also, the heavy stands of phreatophytes often clog the flood channels.

Tamarisk is a particularly aggressive species throughout the Southwest. Because of its high water use, adaptability to flood plain conditions, and rapid spread, this species has created a particularly pressing problem. Some native species are also believed to be wasteful users of water.

The Forest Service research program on phreatophytes aims to determine basic information on: (1) Water use of various phreatophytes in order to select species less demanding of water, and (2) the life history of important species in order to properly control undesirable plants and to establish and maintain the desired cover.

An apparatus utilizing an infrared gas analyzer has been developed for determining evapotranspiration rates of plants growing under natural conditions in the field. Using this apparatus an open stand of tamarisk has been determined to transpire considerably more water than an equal area of Bermudagrass sod.

Tamarisk seeds germinate in free water and become established on warm, moist soils if atmosphere is humid. Seedlings develop slowly and are easily killed by soil drying. Cut stumps or free stem cuttings of tamarisk sprout readily to form new plants if soils are kept moist, but roots do not produce new individuals.

At present, the most successful control of mature stands of tamarisk is by mechanical means in combination with chemicals. Clearing operations should be designed to cut the shrubs a few inches below the soil surface when the soils are dry. This is followed up by chemical treatment of missed or sprouting plants. Young seedlings should be treated with herbicides before they are six months old.

Where practical, cleared areas should be farmed or planted to grass for intensive grazing to maintain a productive cover.

Construction of levees and channelization of flood flows and the regulation of reservoir releases will not only effectively reduce water losses but also prevent tamarisk invasion of formerly flooded areas.

RÉSUMÉ

Les plantes phréatophytes occupent des surfaces considérables le long des rivières et des fleuves ainsi que dans les champs d'inondation dans le Sud-Ouest. Ces plantes consomment de l'eau qui pourrait être mieux utilisée. D'autre part, des masses de ces plantes bloquent souvent les chenaux d'inondation.

Le Tamaris est une espèce particulièrement nocive dans le Sud-Ouest. Par suite de sa consommation considérable d'eau, de sa facilité d'adaptation aux conditions des champs d'inondation et de son extension rapide, ces espèces ont créé un problème particulièrement pressant. D'autres espèces indigènes sont également soupçonnées de gaspiller l'eau.

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Le programme de recherche du Service Forestier sur les plantes phréatophytes tend à établir des informations de base sur : (1) la consommation d'eau de diverses plantes phréatophytes afin de pouvoir classer les espèces exigeant moins d'eau et (2) l'histoire de la vie des espèces importantes afin de pouvoir contrôler les plantes indésirables tout en établissant et en maintenant la couverture végétable désirée.

Un appareil utilisant un analyseur de gaz à rayons infrarouges à été developpé pour déterminer les taux d'évapotranspiration de plantes poussant dans les conditions naturelles en plein champ. L'utilisation de cet appareil a permis de déterminer qu'un massif isolé de tamaris évapore considérablement plus d'eau qu'une étendue égale de « Bermuda-grass ».

Les semances de tamaris germent en eau libre et s'établissent sur des sols chauds et humides si l'atmosphère est humide. Les jeunes pousses se développent lentement et meurent aisément si le sol sèche. Les boutures de tamaris se développent si le sol est humide, mais les racines ne produisent pas de nouvelles pousses.

A l'heure actuelle ; le contrôle le plus efficace des plantes adultes de tamaris se réalise par des moyens mécaniques combinés avec l'emploi de produits chimiques. Les opérations de nettoyage devraient consister à couper les buissons quelques pouces sous la surface du sol quand celui-ci est sec. On procède alors à un traitement chimique des plantes subsistantes. Les jeunes plantes devraient être traitées à l'herbicide avant qu'elles n'aient atteint six mois.

Quand c'est possible les surfaces nettoyées devraient être cultivées ou couvertes d'herbes pour un pâturage intensif afin de maintenir une couverture productive.

La construction de digues et le maintien des crues dans les lits ainsi que lar régularisation par les réservoirs ne réduiront pas seulement les pertes en eau mais préviendront également l'invasion par le tamaris des zones autrefois inondées.

Phreatophytes are plants that grow where their roots can reach the water table or the capillary fringe above the water table. They are found on streambanks, flood plains, and desert washes throughout the arid West. In the presence of a perennial water supply, this vegetation uses water that might otherwise be available for more beneficial uses. In addition, phreatophytes form barriers to flood flows increasing flood stage and deposition of sediment.

Several agencies are participating in phreatophyte removal and research to improve present control methods (*Thompson*, 1957). Recently ecological work has been started on the phreatophyte associations and their component species (*Merkel* and *Hopkins*, 1957) to provide needed information for supression of established stands and to control spread. Also, careful work is being initiated to determine actual water savings possible by replacing phreatophytes with plants more economical in their use of water. The Forest Service started a research program on phreatophytes in 1955. This work is centered at Tempe, Arizona. It is designed to supplement the programs of other agencies.

Research effort of the Forest Service was initially concerned with five-stamen tamarisk (*Tamarix pentandra* Pall.) which has spread rapidly in the last quarter of a century since its introduction from the Mediterranean region. Many thousands of hectares of flood plain and river banks in the Southwest are now occupied by this species.

The research approach of the Forest Service is two-fold: (1) To determine water use of both individual plants and associations of phreatophytes under varying conditions; and (2) to study the life history, ecology, and physiology of the various species as a basis for devising management or control systems. Ultimately these systems should be applied in the field both to create and to

maintain vegetation associations that will have higher economic use than the present cover.

Where Phreatophytes Grow

In the Southwest, riparian sites from the high mountains to the desert regions are occupied by phreatophytes. Associations of phreatophytes of the Southwest tend to intergrade but three broad phreatophyte situations can be distinguished.

The most noteworthy association grows at relatively low altitudes (roughly below 1,800 meters) along perennial streams or over shallow ground water in alluvial deposits. Seepwillow baccharis (*Baccharis glutinosa* Pers.), Fremont cottonwood (*Populus fremontii* S. Wats.), mesquite (*Prosopis* spp.), and arrowweed (*Pluchea sericea* (Nutt.) Coville) are common species forming either dense thickets or open groves. In places five-stamen tamarisk has completely replaced the native vegetation.

Streams at elevations between 600 to 1,800 meters with intermittent flow constitute a second general situation. Arizona sycamore (*Platanus wrightii* S. Wats.), willows (*Salix* spp.), Fremont cottonwood, Arizona black walnut (*Juglans major* (Torr.) Heller.), and inland boxelder (*Acer negundo* L.) are found along these streams at the higher elevations. Tamarisk is rare in this association. Below 900 meters elevation, desert washes of infrequent flow are occupied by mesquite, desertwillow (*Chilopsis linearis* (Cav.) Sweet), and blue paloverde (*Cercidium floridum* Benth.).

In the higher mountains above 1,800 meters perennial streams are characteristically lined with alder (*Alnus* spp.), maples (*Acer* spp.), willows and other minor deciduous species.

Water Consumption by Phreatophytes

Area Estimates

Robinson (1952) estimated that phreatophytes occupy 162,000 hectares in Arizona and that about one billion, seven hundred million cubic meters of water is consumed annually by this vegetation. For New Mexico, his estimates are 178,000 hectares of phreatophytes and a consumption loss of slightly more than one billion cubic meters. For the 17 western states, *Robinson* (1958) estimates that phreatophytes may occupy as much as 6,474,000 hectares and consume nearly 31 billion cubic meters of water annually.

Stream Losses

Estimates of water loss have also been made for several stretches of streams. For a 74 kilometer reach of the Gila River below Safford, Arizona, that is lined by phreatophytes, 1,547 cubic meters per hectare are estimated to be consumed (*Gatewood* and others, 1950). Along a stretch of Coldwater Canyon in California, average water loss per hectare from 2.384 hectares of canyon bottom from July 15 to October 31, 1932, was found to be 12.48 cubic meters per day (*Blaney* and others, 1933). At a higher elevation in the Wasatch Mountains of Utah, evapotranspiration losses from Farmington Creek amounted to about one-third of the total flow during the later summer (*Croft*, 1948).

Lysimeter Measurements

Lysimeters have been used to measure consumption by individual species of phreatophytes. Tank measurements were made for different species in 1940 at Safford, Arizona. In this study, tamarisk used somewhat more water than seepwillow baccharis. Also, water use decreased markedly as the water table was lowered (*Turner* and *Halpenny*, 1941). Tanks with vegetation gave considerably higher evaporation losses than tanks maintained under the same conditions but without vegetation. These results were verified by similar studies at the same locality in 1943 and 1944 (*Gatewood* and others, 1950).

Estimates of water loss from lysimeter studies should be applied with caution to field conditions. Plants grown in artificial conditions may differ markedly in their characteristics from those growing under field conditions. Also, there is often considerable variation from one tank to another, and oftentimes replications are insufficient for statistical reliability.

Vapor Loss Measurements

Vapor measurements can be used to determine evapotranspiration losses from individual plants or groups of plants and to determine the various factors influencing evapotranspiration rates. A device being used by the Forest Service employs an infrared gas analyzer to measure humidity differences in air entering and leaving a tent enclosing a plant. Transpiration and photosynthesis rates were first measured from leaves or shoots sealed in a small chamber (*Decker* and *Wetzel*, 1957). A larger tent constructed of polyethylene film was first tested under field conditions in 1958.

In the field, paired tents are placed over adjacent plots and ventilated at a known rate by radial-flow fans powered by gas engines. The tents are inflated and held in place by air pressures created by the fans. Vapor content of air entering and leaving the tents is measured by the infrared gas analyzer. The humidity difference times the ventilation rate gives vapor production within the tents. The analyzer and the entire apparatus have been standardized and calibrated against known atmospheric conditions so that absolute amounts of vapor loss can be computed.

Measurements with this equipment indicate that tamarisk transpires considerably more water than Bermudagrass sod under similar climatic and environmental conditions.

Fluctuations in Ground Water Elevations

White (1932) estimated the water used by various plants from a study of the daily fluctuations in ground water level. He observed that during the growing season there was a marked daily fluctuation of the water table nearly everywhere in fields of ground water plants. Usually the water starts down between 9h 00m and 11h 00m and falls until 18h 00m to 19h 00m. A rise in level begins between 19h 00m to 21h 00m and continues until the next morning. He devised methods of estimating inflow rate and from this rate and the specific yield of the soil calculated water use. The method depends on careful technique. Precautions and correction factors are discussed by *Gatewood* and others (1950).

Basic Ecological Information

The second part of the Forest Service program is designed to determine the life history and ecology of the important phreatophytes. Studies so far have included work on seed germination, seedling establishment, sprouting ability, plant succession, and effect of livestock utilization.

Seed Germination

Many phreatophyte species produce numerous, small, wind-blown seed. For example, on the Salt River east of Phoenix, Arizona, large quantities of tamarisk seed are produced from April through September. Maximum production is reached in May and June. On the Pecos and Rio Grande Rivers of New Mexico where the altitudes are higher, seed production is delayed until the middle of May.

Fresh seed of tamarisk often shows a rate of germination of 100 %. Seed will germinate within 24 hours after moistening. Viability of tamarisk seed is short. Seed collected in the early summer and stored at 24° to 27° C shows markedly decreased viability in 6-10 weeks. Seed of late summer holds good viability for nearly a year. Temperature as high as 35° to 40° C kills the seed rapidly.

Seepwillow seed germinates more slowly than tamarisk seed, but remains viable for a longer period. Arrowweed seed is comparable to that of seep-willow. Fresh seed of cottonwood is highly viable but deteriorates in a few weeks.

Tamarisk seed germinates on water during warm temperatures. They will also germinate on warm moist soil if the atmosphere is very humid. During May and June all free water surfaces of such rivers as the Salt and Verde of Arizona contain floating germinated seeds. These seedlings will float to the shore and, if stranded by receding flow, become established in the saturated soil.

Growth and Development of Tamarisk Seedlings

Seedlings of tamarisk are only 1 mm in size at germination. Development is slow. At four weeks, seedlings grown in the greenhouse averaged only 1.9 cm in height and roots were 4.0 cm in length. In the following two-week intervals shoots increased to 6.6 cm and 11.7 cm. Measurements of roots during comparable periods were 6.3 cm and 15.6 cm.

Because of slow development of the seedlings they cannot survive except under ideal conditions. Under greenhouse conditions, seedling establishment was successful only on saturated soils at temperatures somewhat above 25° C. Seedlings did not become established on soils which were watered daily and then allowed to drain to field capacity.

Tamarisk seedlings are not drought resistant. Two-month old seedlings of tamarisk will not survive more than one or two days after they reach a stage of wilting. Seepwillow is slightly more drought resistant than tamarisk.

Seedlings of tamarisk will survive long periods of submergence. Six weeks of complete submergence were needed to injure or kill tamarisk seedlings in the laboratory.

Sprouting Ability

Tamarisk sprouts vigorously from cut stumps or from stem cuttings. During the growing season almost all stem cuttings of various sizes produced roots and formed new plants under greenhouse conditions. Sprouting ability was greatly reduced during the winter.

Root cuttings produced roots but no shoots and soon died from lack of photosynthetic tissue. Under field conditions sprouts do not form from severed roots. Only crown or stem material left in the ground will form new plants.

Successional Trends

The most striking change in the phreatophyte areas of the Southwest is the aggressive spread of tamarisk. The species invades bare sediments of aggrading stream channels. Elsewhere, tamarisk spread is much slower.

Control of Phreatophytes

Several methods have been tried with varying degrees of success for the control of phreatophytes, particularly tamarisk. Much is yet to be learned about control procedures, species to be used for replacement, and their management. Among the methods of control that have been tried are mechanical clearing by bulldozing, root plowing, and discing; application of chemicals; and lowering of the ground water table.

Mechanical Control

Tamarisk and associated phreatophytes have been cleared by bulldozing, discing, or root plowing large areas of the Rio Grande, Pecos, and Gila Rivers (*Lowry*, 1957, *Fletcher* and *Elmendorf*, 1955, *Bowser*, 1952). Success has been variable. Most failures can be traced to the vigorous sprouting ability of tamarisk stems during the growing season. Any stems buried in wet soil give rise to new plants.

Root plowing has proved to be a cheap and effective control method. This technique severs shrubs below the root crown, does not form depressions for collection of water, and does not bury natural herbaceous cover. If the work is accomplished when the soil is dry and the weather warm, severed tops of the shrubs fail to sprout even if buried.

Chemical Control

Tamarisk is generally quite resistant to the common systemic herbicides (*Arle*, 1957). Three or more applications of herbicide over a period of two years are required to eradicate mature tamarisk. Regrowth and seedlings (six months old or less) are more readily killed than plants a year or more old. A single application of 2.3 kilograms per hectare of 2,4-D will kill young plants. 2-(2,4,5-trichlorophenoxy) propionic acid (Silvex) is more effective than 2,4-D or 2,4,5-T, or a mixture of the two.

At present the most effective method of eliminating a stand of tamarisk is to clear mechanically, to burn debris, and to treat regrowth with chemicals

after several months. When regrowth is sparse, individual shrubs can be treated. Thus, the more effective the mechanical treatment, the less followup by chemical treatment that will be needed. Tamarisk seedlings should be sprayed with herbicides before the seedlings are six months old for effective control.

Water Control

Lowering water-table levels will reduce amount of water lost both by transpiration from phreatophytes and by evaporation from soil surfaces.

Prevention of flood flows from spreading over flood plains by means of channelization and levees also avoids the possibility of establishing tamarisk seedlings. Water releases from reservoirs can sometimes be used to control tamarisk invasion of stream channels below the dam.

Replacement Species

After clearing of the undesired phreatophytes, other species, often equally undesirable, will in time naturally invade the cleared area. Therefore, provision must be made for management of such cleared lands. In some areas cultivation and planting of crops are possible. Establishment of a sod forming grass may create conditions unfavorable for the return of phreatophytes. Bermudagrass appears to be a suitable species for this purpose. Cattle grazing on Bermudagrass also browse new growth of tamarisk, reducing vigor of established plants.

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SYSTEMATIC AND NOMENCLATURE OF WATER-BALANCES

by Dr. JULIAN LAMBOR, Warsaw

SUMMARY

The author offers his suggestions concerning the systematization of various water balances and their different forms, describing concisely each separate type.

RÉSUMÉ

L'auteur présente ses suggestions concernant la systématisation des divers bilans d'eau sous leurs diverses formes et en décrit brièvement chaque type.

The hydrology section dealing with water balance has lately developed more and more. A new science has been created which now needs to be systematized owing to the fact that various authors apply a nomenclature which does not always involve the same ideas and this often causes misunderstanding.

The general definition of water balance is no longer sufficient and it is necessary to define each separate kind of water balance more closely and precisely. This is specifically important for the planning of water economy.

In the present state of this science it appears advisable to establish the following division of water balances.

1. Original or historical water balance
2. Dynamic water balance
3. Natural or raw water balance, which may be:
    a) full water balance
    b) stock water balance
4. Usable water balance
5. Planned Water Balance
6. Perspective water balance
7. Operative water balance.

1. Original or historical water balance—a period of centuries now passed but in the range of today's geological epoc.
Original water balance consists of the reconstruction of hydrological conditions (e. g. of the Middle Ages) which do not now exist.
The aim of this balance is not only to obtain a knowledge of the former ancient conditions of water circulation, but, more important, to grasp the trends of development and evolution in today's hydrologic conditions.

2. Dynamic balance—ought to enable one to foresee the changes which will take place in the future in the system of hydrologic conditions of specific areas, due to various factors. These changes will be mostly over long periods. Dynamic water balance enables changes occurring in the biocoenosis of an area to be understood together with such phenomena as, for instance, steppe forming.

On the other hand, the changes we observe in flora and fauna—where one species give way to another—testify the dynamic long period changes in water balance. An important part is also played by wooded areas and forest structure.

3. Natural balance—also called raw balance includes the research of natural water stocks and losses within a definite area, and period, without going into the problems of demand and ways of usage of these water stocks.
This balance then will consist of a registering of the in-flow and out-flow which the regions under research obtain in the form of rainfall, as well as in establishing losses without taking into account the problem of water used and the kind of users.
In the natural balance, no artificial changes in water circulation are considered. Natural balance does not contain the elements of artificial steering of water circulation. If, however, there occurs an artificial affectation which is not to be separated, then we shall deal with a raw but not natural balance.
Natural or raw balance may include the calculation of all terms of the balance equation:

$$P = H + V + \triangle R$$

i. e. rainfall out-flow vaporation and retention.
The "full raw balance" or, if we confine this to only two elements illustrating the disposable water stocks, i. e., rainfall and out-flow, then this will be a "raw stock balance" ($P - H = S$) which, in short, we call "stock balance". However, this is not a balance in the full sense of the word.
By the term "natural or raw balance" we usually mean a full balance, that is, stock balance including calculation of vaporation and retention.

4. Usuable water balance—illustrates not only the existing state of water stocks but also the actual state of utilizing these stocks. So it does not confine itself to registering the stocks and reserves of water, but also considers the utilisation of these stocks and the water demand.
The usuable balance illustrates the existing state without going thoroughly into any changes but this still belongs to the category of statistic balances as opposed to dynamic balances and illustrates changes arising in the circulation and occurring in the utilization of water.

5. Planned balance—enables the utilization of water stocks to be foreseen and leads water economy according to the plan for the economic development of the whole area. This is comprised in the water balance as well as the stock possibilities established by a water economy plan. Accordingly, this is a dynamic balance not actual but foreseen. The balance period in the planned balance usually conforms with the period of the general economic plan and mostly consists of a 5-year period.

6. Perspective balance—is also a planned balance but is of a long period, usually 25—30 years. This balance is based on the general water economy plan and not the detailed plan; so the jist of this plan lies in foreseeing the changes which occur in water conditions during the realization of the general plan.

7. Operative balance—gives the effect of the planned balance in practical application. This balance is based on the steady registration of the performing process of the balance, taking especially into consideration the over-sizes, deficiencies, barren droppings, production quantity and degree of impurities, etc.

Lists and notes made within the operative balance serve to control the idea of what can be anticipated in the planned balance and giving a basis for improving the plan of water supply and utilization.
Besides this the operative balance enables a water supply at the earliest possible period for the purpose of production planning to be foreseen.

WATER AND WOODLANDS: INVESTIGATIONS IN THE UNITED KINGDOM INTO THE WATER RELATIONSHIPS OF WOODLANDS, AND THE PROBLEM OF MEASURING RAINFALL OVER WOODS

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Eau et régions boisées: Des investigations dans le Royaume Uni, sur l'hydrologie des régions boisées et le problème du mesurage de la pluie dans les bois.

SUMMARY

A brief outline is given, against the historical background, of investigations in the U. K. at present in progress, or known to have been proposed, into the hydrological problems associated with afforestation. The problem of the accurate measurement of rainfall over woods is chosen for special mention, in relation to the general problem of the accurate measurement of precipitation, in which there is currently renewed interest in the U. K. and elsewhere.

RÉSUMÉ

L'auteur donne une courte esquisse historique des investigations qui sont à présent en cours d'exécution dans le Royaume Uni, et de celles que l'on sait qu'on a proposées, sur les problèmes hydrologiques qui s'associent au boisement. Le problème du mesurage précis de la pluie dans les bois est spécialement choisi, relativement au problème général du mesurage précis des précipitations qui actuellement éveille un intérêt renouvelé dans le Royaume Uni et ailleurs.

Until recent years there was no great practical interest, in the U.K., in the hydrological problems associated with afforestation of the gathering grounds of water-supply reservoirs. Although in an authoritative survey of British waterworks practice (1), it is stated that "afforestation of catchment areas appears to have started at Oldham in 1885", yet more than 60 years after that date it was possible to write (2): "A recent survey of the problems of afforestation in twenty-eight of the larger water-supply catchment areas in Britain reveals a dismal picture. In only one is 20 per cent of the area afforested, and thirteen have no land under forest".

In the meantime some papers dealing with the subject had been presented in British journals, though they seem to have been rather sparsely distributed. Davidson in 1925 (3) and Rodwell in 1936 (4) were among the few authors concerned up to the publication of an official report in 1948 (5). Attention had been directed largely towards the role of woodlands in moderating floods and in reducing erosion and pollution, and it was, to a great extent, the requirements for pollution control which gave rise to the official report. The sub-committee responsible also had in mind the importance of maintaining agricultural production at the highest possible level, and recommended that, subject to adequate control of pollution, gathering grounds should be put to the fullest agricultural use. Where conditions were not favourable for agriculture, it was recommended that gathering grounds should be afforested.

In the next few years Lloyd (6, 7) and Thompson (8) advanced conclusions derived from experience in partially afforested gathering grounds which appeared to show that no serious effects on water supplies resulted from

afforestation. The former stated: "the data from the Vyrnwy catchment provide no evidence for inference that afforestation has effected the hydrology of the drainage area", and more specifically: "the records of the Vyrnwy catchment of 23,290 acres, where the acreage afforested had been increased from 3 per cent to 20 per cent of the catchment" showed "that over a period of years, afforestation had no discernible affect on the quantity of long-period run-off". There was, however, a quite perceptible affect in the moderation of peak discharges from isolated rainstorms. The latter considered: "On the whole, the indications are that the total loss by evaporation from a large wooded area is not significantly greater than from the same area of grassland, or moorland.....the net yield from a gathering ground is unlikely to be either increased or reduced to an appreciable extent by afforestation of even the whole area".

These views were broadly in harmony with others which were advanced at about the same time in a rather different context, associated especially, in Britain, with the work of Penman. In order to calculate with some precision irrigation needs for optimum crop production, a method was developed for estimating evaporation from growing crops, using meteorological data. The scope of the work was reviewed at an informal meeting on physics in agriculture at Wageningen in 1955, the report of which (9) includes a summary of the conclusions of the discussion and the assumptions involved. Thus it was there stated: "the maximum rate of evaporation.....is determined primilary by weather. With certain restrictions, this maximum rate appears to be largely independent of the kind of crop or the kind of soil on which it is growing". Whilst this view was not universally accepted as applying equally to woodlands, as well as to the short field crops referred to in its original context (and even there conflicting evidence was advanced (10)), it can be said that up to this time the policy of afforestation of gathering grounds, recommended in the report of 1948, was pursued without much concern for any possibly adverse effects on water supplies.

Shortly afterwards, in 1956, Law (11, 12) introduced a totally contrary opinion, based on experimental work which seemed to show that the effective yield from a reservoired gathering ground might be decreased by about a third, or even a half, by the afforestation of the whole area. Law himself recognized that his results, derived from data obtained in a very small plantation of a particular species, could perhaps not be validly generalized, and applied to extensive areas of forest. But he presented his views so provocatively that within a year or two there was, in the U.K., very rapid growth of interest in the entire problem of the water relationships of woodlands.

An attempt to qualify the conclusions reached by Law has already been made elsewhere (13), and the arguments will not be repeated. It must be said, however, that his continuing experiments are producing valuable data in a variety of ways, and whatever may be the ultimate decision regarding his main conclusion so far, he has already performed a most useful service by stimulating interest in the U.K. in this type of investigation. There is now a much wider appreciation that economically important problems exist, problems which have a very close bearing on the conflicting demands of agriculture forestry and the water-supply industry for land and for access to the interdependent resources of soil moisture and surface water, and that serious efforts must be made to solve them.

Some of the investigations which are now in progress in the U.K. are dealt with in other papers contributed to this Symposium. Rutter of the

Imperial College, University of London, and Leyton and Carlisle of the Imperial Forestry Institute, Department of Forestry, University of Oxford, have initiated work of a fundamental nature which, like the work of Law, is designed to explore the details of the behaviour of water in afforested areas. The alternative of a long-term statistical approach has also been considered, and investigations of this kind have been proposed and indeed, in at least one area, begun. It will require several years, during which the rainfall and run-off relationships of afforested and control areas will be compared, before even a preliminary report of any of these investigations can be produced in the U.K. It is of special interest, however, that the first initiative in this respect came form Northern Ireland. Proposals have there been made for investigations on three gathering grounds, including the Woodburn Reservoirs area of the Belfast Water Commissioners where the work was started in 1958. It is perhaps a measure of the seriousness with which the problem is now viewed by water engineers, that the first steps of this kind were taken in a province traditionally thought to suffer no lack of moisture. The Forestry Commission is also actively considering similar investigations, and an afforested area in southern Scotland has been suggested as one possible site.

Many of those now concerned with afforestation investigations in the U.K. are giving much thought to the problem of rainfall measurement over woods. There is in fact a growing realization that in hydrological work in general it is necessary to give careful consideration to the measurement of precipitation, in particular to consider whether rain-gauges exposed according to the long-established British standards provide sufficiently accurate data, or whether there is a need to make more specialized observations in some situations. The Meteorological Office is concerned with this problem in a number of ways, and is co-operating in various attempts to measure rainfall on non-standard sites, recognizing that in hydrology there is a need to consider the absolute accuracy of measurements in many different circumstances, and not merely, as might be argued meteorologically, a need for comparable measurements from conventionally standard sites.

The most advanced investigations as yet are those being made by Law with the object of determining the actual rainfall falling on a small plantation. From the beginning, an attempt was made to assess the fall by taking the mean from three rain-gauges exposed in the standard manner at ground level, in open situations near the plantation and in different directions from it. But gauges with or without shields were also set up on poles within the wood, with their rims at or near to the height of the canopy. Several adjustments of height were tried experimentally to determine the effects on catch. Comparative experiments, with gauges on poles at various heights up to 30 feet above ground level, are now being pursued on an open site near the wood, in an attempt to assess the effects of wind speed and turbulence on the catch of elevated shielded gauges. It is hoped that it will be possible to present some of Law's data of this type at the Symposium, but one of the most interesting data series is of very recent origin, and it is not at present certain that sufficient data will be available in time.

It can hardly be disputed that turbulence over a small wood is likely to produce a distribution of rainfall different from that which would have occurred in the absence of the trees, and that it is strictly necessary to measure rainfall on the canopy itself in small-scale investigations of this kind. Leyton and Carlisle draw attention to this matter in general terms,

without specific reference to the size of the wooded area, and the subject has also been touched on recently in unpublished papers by research officers of the Forestry Commission. There is another important situation which should perhaps be specifically mentioned, representing the physical opposite of a small wood in open country. In some afforestation investigations rainfall has been measured by exposing rain-gauges in small clearings within large forests, and the data have been considered acceptable. It is highly improbable that the distribution of rainfall in the neighbourhood is unaffected by turbulence caused by the clearing, and it is unlikely that rainfall measured on such a site is representative of that which falls on the surrounding canopy except in very light winds or calms. During preliminary discussion of the proposed investigations in Northern Ireland it was suggested that where rain-gauges were to be installed in areas to be afforested, small clearings should be left surrounding the gauges. The forestry officer present pointed out that there was a serious objection to this suggestion, quite apart from the economic loss due to non-planting in the clearings; it is often observed that damage due to strong winds or gales begins in such places, more so than at the edges of forests. This can only mean that a clearing causes peculiar conditions of turbulence, which must also be present in milder form even with the more moderate wind speeds which do not cause actual damage to the trees. The attempted measurement of rainfall in a clearing cannot therefore provide representative data for the rainfall amounts received at the uninterrupted canopy. Even the most exhaustive investigations of the details of rainfall distribution at ground level within clearings, or near the edges of forests, could not provide an adequate solution. For any accurate determination of the water budget of woodlands an acceptable method of measuring rainfall at the canopy itself must be found. This is likely to be a most formidable problem, since even the standard measurements of rainfall at ground level are being increasingly questioned (14), and it must be admitted that verified absolute measurements of rainfall have not yet been achieved.

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FOUR YEARS' EXPERIENCE IN ATTEMPTING TO STANDARDIZE MEASUREMENTS OF POTENTIAL EVAPO-TRANSPIRATION IN THE BRITISH ISLES AND THE ECOLOGICAL SIGNIFICANCE OF THE RESULTS

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SUMMARY

Further lessons have been learned from the network of observations of potential evapo-transpiration in the British Isles, which were described at the Toronto Conference. With reservations, these support the view that in the North-West European climate: (i) PE from a grass sward is the most representative standard for this parameter, (ii) values of PE computed by formula are suitable for some purposes but not others, (iii) with observed values of PE it is possible to compute water deficits and surpluses even though the accompanying rainfall measurements are suspect. Amounts and incidence of water deficit are of paramount importance ecologically.

RÉSUMÉ

On a continué à récolter des informations très utiles au moyen du réseau d'observations de l'évapo-transpiration potentielle, qui était le sujet d'une contribution présentée à la conférence de Toronto. Avec certaines réserves, celles-ci soutiennent l'opinion que, dans le climat de l'Europe de nord-ouest, (i) l'EP d'un gazon est le montant le plus représentatif de ce paramètre, (ii) les valeurs de l'EP, obtenues par formule, sont convenables pour certains buts mais pas pour d'autres, (iii) avec des valeurs observées de l'EP, il est possible d'évaluer des déficits et des surplus de l'eau, même quand le montant des pluies est suspect. Les montants et l'incidence des déficits et des surplus de l'eau sont d'importance extrême pour l'écologie.

In assessing the accuracy of a piece of observational apparatus, and the value of the observations made with it, it is desirable to set up (a) a series of parallel observations at a "pilot station", and (b) a network of observations made with one or more of the methods used at the pilot station. In the case of measurements of evaporation, especially of potential evapo-transpiration, it seems fair to say that more attention has been given to (a) than to (b). It was mainly in order to find out what could be learned from a network, at sites chosen to be in different climatic settings, that the Nature Conservancy have taken observations over the last few years at the places shown in Fig. 1. The observations now collected since 1954 reveal a number of quite diverse points of interest. The technique of making, and of recording, the observations has been discussed elsewhere, and will not be repeated here (Green 1958). It is worth stating here, however, that the results obtained from the very cheap and simple apparatus employed exceeded expectations, and a theme underlying this present paper is that this kind of network is well worth developing.

All the measurements described have been made in respect of a homogeneous sward of grass or physically similar vegetation. The justification for using this as a *standard* setting is based on the following considerations:

(i) the energy-balance conception, as demonstrated particularly by Penman, indicates that any homogeneous surface will react in much the same way so long as water is not a limiting factor.

(ii) a study of *rainfall minus run-off*, for a large number of catchment areas, indicates very strongly that the evaporation "loss", during periods when water is not a limiting factor, is much the same as that either computed or observed in respect of an area of grass sward, i. e., the grass-sward evaporation is about the *norm*, whether or not the energy balance deductions are correct.

(iii) the grass-sward site is that internationally accepted as *standard* for other meteorological observations; this facilitates comparisons between all meteorological elements concerned

It is submitted that observations made in respect of a grass sward are, for the above reasons, better for many purposes than "open water" observations, particularly when one is dealing with the land as opposed to the ocean.

One technical difficulty that must be referred to is that the potential evaporation (PE) observations do depend upon accurate measurement of the rain falling on to the field tank, i. e., on to what is to all intents and purposes the natural surface. The rainfall has, in fact, been measured in raingauges exposed according to standard specifications (with rims 1 foot above the ground level). But only in "ideal" circumstances can it be assumed that what is measured in such a gauge is the same as that falling on the field tank; the more exposed the site and the higher the wind speed the greater can the divergence be expected to be. With PE *observations*, however, which depend on such rainfall measurements, the error is cancelled out when one calculates *water deficit* and *water surplus;* this is not the case when PE is *computed*, since the measured rainfall then appears on one side of the equation only, and not on both. This argument is in itself alone a strong case for measuring PE rather than computing it! Fig. 2 shows in graphical form the 1957 and 1958 observed PE and observed rainfall at stations in the network. Figs. 3 and 4 show water deficits and water surpluses obtained by subtracting rainfall from PE which itself is $R + A - N$, (where R is precipitation, A is irrigation water added, and N is percolate), and so eliminating R, which may have been measured incorrectly. One is, in fact, relying solely on measurements of A and N, which can be confidently regarded as accurate.

There emerges from Figs. 3 and 4 a clearly intelligible correlation with geographical location. 1957, though perhaps with a somewhat higher-than-average rainfall over Scotland and Ireland, was a fairly typical year in the British Isles as a whole. Wellesbourne, representing the South, shows the effect of high summer temperatures over-riding the effect of the summer rainfall maximum, especially in *early* summer.

Lossiemouth represents a dry east coast station, where the midsummer temperatures and long daylight have not been high enough to offset the effect of summer maximum rainfall. Temperatures and relatively long days have, however, been great enough to lead to a water deficit during the early summer and autumn rainfall minima. At neither of those stations is the *water surplus* large.

Swyddffynnon is the nearest approach to a typical southwestern station in England and Wales, and in 1957 was very similar to Valentia, the southwest Irish Station. Both have a striking winter maximum rainfall with a small subsidiary maximum in late summer. Thus, the 1957 water deficit occurred in spring and early summer; there was no second water deficit period in the year, but there was in the late autumn a period with only a

small surplus. Swyddffynnon and Valentia differ from Wellesbourne and Lossiemouth in having a considerable water surplus.

All the places mentioned above are surrounded by agricultural land (i. e. land in rotation cultivation and "improved" grass). Prabost, which is seen to have had only a very small water deficit — in June — in 1957, is on the margin of cultivation. It here seems appropriate to suggest that a short period of "water deficit" in the year is of great significance to agricultural land use; no amount of field drainage can dry the soil at all if water is being added faster than it is removed, and evidence is accumulating that a short period of water deficit (i. e. of PE exceeding rainfall) is of enormous ecological significance. Kinlochewe had no such period in 1957, and it is in a location which is closer to the agricultural margin than Prabost; its actual site is, in fact, just beyond the margin, but some adjoining, better sited land, is in cultivation.

In this connection, one may observe that Thornthwaite shows Zürich, in Switzerland, as having no period of water deficit. It is difficult to believe that this is correct. Could the Canton Zürich be as well cultivated as it is if both Thornthwaite's computed PE were correct and the rainfall measured in the standard gauges representative of what fell on the ground? Some light is shed on this problem by noting the PE at Achnagoichan (1,000 feet) and Moor House (1,850 feet), the most elevated stations in the network. Both, in 1957, had small water deficits; the observed PE appeared to be higher in the critical months than that computed by formula. Cultivation, in fact, takes place at both sites, but at Moor House is limited by lack of soil. One is permitted to ask whether the lack of soil may possibly be connected with a historical period when in average years there had been no water deficit.

1958 was a year which, particularly in the summer, was much wetter than the average, except in the extreme north-west of the British Isles. As a result, Valentia and Moor House had no periods of water deficit (in the case of Valentia this had not happened at least since 1951). Achnagoichan, and the English and Welsh Stations, had much smaller water deficits than in 1957, while the north-western stations of Prabost and the Isle of Rhum had quite distinct periods when PE exceeded rainfall, and when Kinlochewe had two calendar months with an even balance.

It is hoped that enough has been said above to demonstrate the probability that the network of PE *observations* provides data for ecological study which cannot be provided by *computation* of PE. Nevertheless, the observed values differ from values computed by, e. g., Penman's formula, or Crowe's adaptation of Thornthwaite's formula, by amounts which are sufficiently small for one to have confidence in using the computed values for such practical purposes as estimating required amounts of irrigation water.

An interesting thing strongly suggested by the 1958 observations is that potential evapo-transpiration from a grass sward is practically the same as that from evaporation pans. Thus, observations by the two methods, side by side, at Wellesbourne shows a difference of but half-an-inch through the year, and the Eskdalemuir (see Fig. 1.) evaporation pan "losses" fit perfectly into the geographical pattern of the stations in the PE network. It is suggested that this is because in 1958 the upper layers of the soil were always wet enough for the combined evaporation and transpiration from a grass sward to be equal to the evaporation over open water. Does Penman's reduction factor f become operative only when this condition is not fulfilled, when it becomes a sort of empirical estimate of how much actual conditions fell short of such fulfilment?

During the periods of water deficit, which, normally, correspond in northern and central Europe, with the most active growth period, different types of soil and subsoil have different effects. The natural response to these differences, and the way in which the cultivator and forester, etc., make use of them is a vast study in itself. Yet the most fundamental dividing line in land use, natural or otherwise, may prove to be that between localities which have a period of water deficit at all, and those which have not.

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Fig. 1 Approximate locations of stations observing potential evapo-transpiration. Wellesbourne is operated by the National Vegetable Research Station, Valentia by the Irish Meteorological Service, Coalburn by Captain J. Ross, and Eskdalemuir by the British Meteorological Office.

1957

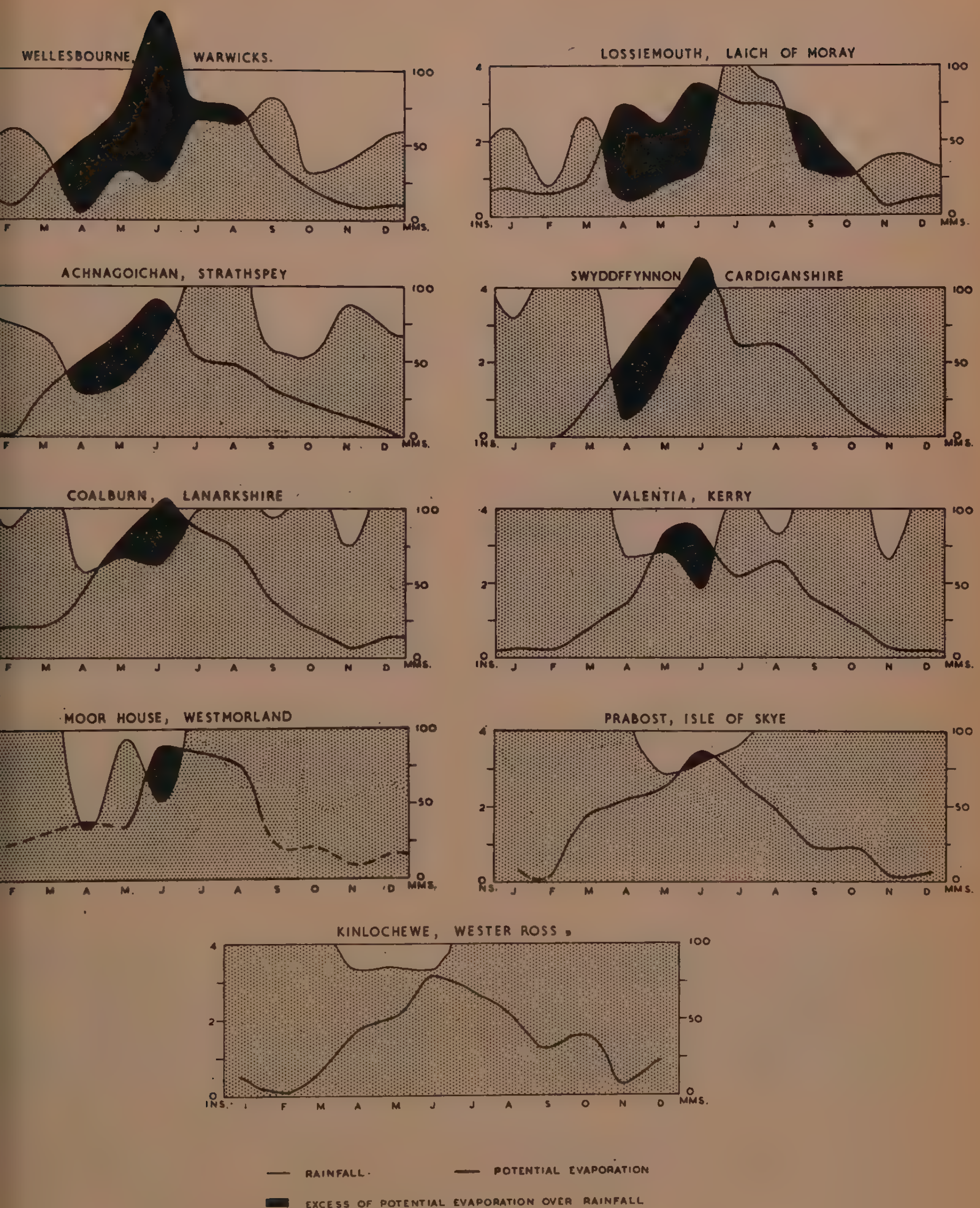

Fig. 2 1957 Observations of Rainfall and Potential Evapo-transpiration.

1958

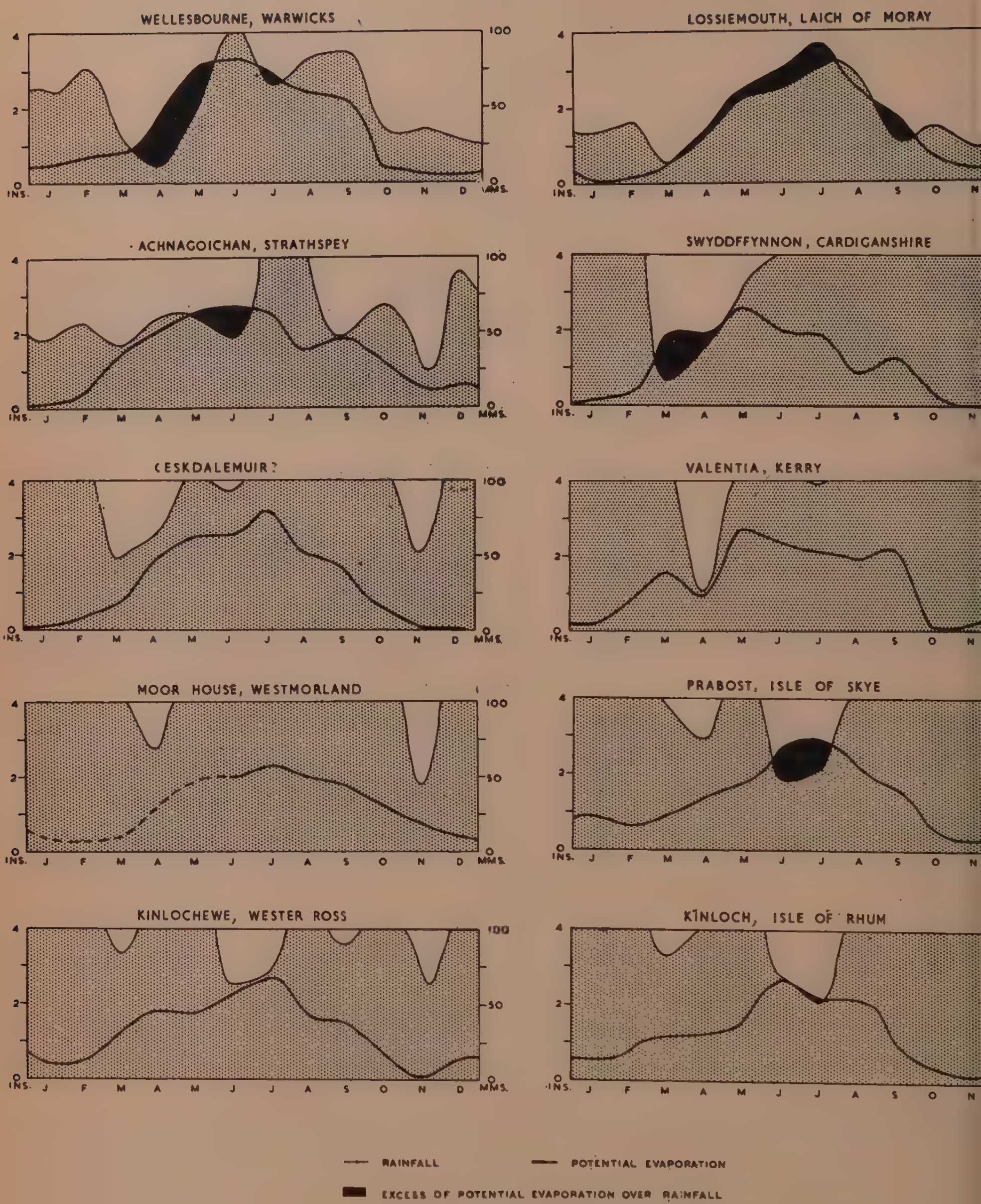

Fig. 3 1958 Observations of Rainfall and Potential Evapo-transpiration.

Fig. 4 Water "Deficit" and Water "Surplus" from month to month in 1957, assuming no water storage.

Fig. 5 Water "deficit" and Water "Surplus" from month to month in 1958, assuming no water storage.

EVAPORATION FROM A PLANTATION OF PINUS SYLVESTRIS IN RELATION TO METEOROLOGICAL AND SOIL CONDITIONS

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SUMMARY

In a plantation of *Pinus sylvestris* 7—10 m. high and with closed canopy, three methods of measuring total evaporation have been compared and found to agree satisfactorily. A method based on observations with tensiometers or resistance blocks is very simple to use and should be applicable in the summer months in most conditions except where the vegetation can draw on ground water. Another method in which interception, evaporation from the soil and transpiration from detached shoots are separately measured, allows an analysis to be made of the relation of these components of evaporation to meteorological and soil conditions.

Evaporation from the plantation was fairly closely related to Penman's estimate of the potential transpiration of grass, but exceeded it in April-September, 1957 by 15 % and in April-September, 1958 by 36 % (Table 1 and Figure 2). The meteorological observations, however, were made at some distance from the forest site.

On small plots within the plantation it has been possible to modify soil moisture conditions. On a plot where entry of rain into the soil was prevented by a cover of roofing felt, the calculated soil water deficit rose to nearly 20 cm. in September, 1958. This did not appreciably reduce the transpiration rate compared with an irrigated plot which was maintained near field capacity. It has not yet been possible to determine the soil moisture conditions which will limit transpiration.

At least in winter, the rate of evaporation of intercepted water exceeds by several times the transpiration rate.

RÉSUMÉ

Dans une plantation à frondaison épaisse de *Pinus sylvestris* de 7 à 10 mètres de haut, on a comparé trois méthodes employées pour mesurer l'évaporation totale et on a trouvé que les résultats concordaient d'une façon satisfaisante. Une méthode fondée sur des observations faites à l'aide de tensiomètres ou « blocs de résistance » est d'application facile pendant l'été dans la plupart des conditions, sauf dans les cas où la végétation peut utiliser l'eau souterraine sous la nappe. Une autre méthode dans laquelle l'interception, l'évaporation du sol et la transpiration de pousses détachées sont mesurées séparément, permet de faire une analyse de la relation de ces facteurs d'évaporation avec les conditions météorologiques et l'état du sol.

L'évaporation de cette plantation a été en relation assez étroite avec l'évaluation de Penman pour la transpiration potentielle de l'herbe, toutefois la dépassant de 15 pour cent dans la période avril-septembre 1957 et de 36 pour cent dans la même période en 1958 (table 1, fig. 2). Cependant les observations météorologiques ont été faites a quelque distance de la plantation.

Sur des petits parties de terrain à l'intérieur de la plantation on a pu modifier les conditions d'humidité du sol. Sur une partie où l'on a empêché l'entrée de la pluie par une couverture de carton goudronné, le déficit d'eau du sol obtenu par calcul est monté à plus de 20 centimètres en septembre 1958. Ceci n'a pas réduit de façon notable le taux de transpiration comparé à celui d'un endroit irrigué qui a été maintenu à la capacité de repletion au champ. Il n'a pas encore été possible d'établir les conditions de teneur d'eau qui pouvraient limiter la transpiration.

Au moins en hiver le taux d'évaporation de l'eau interceptée dépasse plusieurs fois le taux de transpiration.

Introduction

Evaporation from forest or afforested plots has in the past been estimated from the difference between rainfall and run-off both in large lysimeters and on suitable catchments. The disadvantages of these methods are on the one hand that they are too cumbersome and costly for the investigation of the large numbers of comparisons which may be of interest e. g. between different tree species, soil types or methods of culture, and on the other hand that they do not readily yield estimates of evaporation for periods short enough to allow analysis of the effects of sessonal changes in meteorological and soil conditions. The object of the work here described is the comparison of some methods which, though possibly lacking something in precision or universal utility, are nexpensive and do not restrict those who adopt them to the study of a very limited range of conditions.

The work has been carried out in a coniferous forest at Crowthorne, Berkshire, and in particular in a plantation of *Pinus sylvestris* of about ten hectares which is itself surreounded by other plantations of the same species and differing only a little in age and height. The trees were planted in 1941 and are now 7—10 m. high. The canopy is closed and, for this species, dense; its dry weight is about 10,000 Kg./hectare. The upper 60 cm. of the soil is sandy, but below is a fairly heavy sandy clay which shows, however, a vertical drainage system formed partly by the cracks between columnar structural units and partly by old root channels. Sixty-three percent of the root weight of the trees is found in the first 30 cm. of the soil and a further twenty-five percent in the next 30 cm., but numerous roots extend to 120 cm. and a few to 180 cm. Drying of the soil to this depth has been observed.

Within the plantation a square of about 1/6 hectare was marked out for intensive study and subdivided into four plots, in each of which the same series of measurements have been made in order to provide replication. In 1947 the work consisted simply of an investigation of gains and losses of water, without any experimental modification of conditons. This programme was continued in 1948 and in addition three sub-plots, each 9 m. square, were selected for smilarity and uniformity within one half of the experimental area, and were subjected to contrasted soil water conditions. On one the soil was covered with a screen of roofing felt, carefully supported and sealed round the trunks of the trees, so that no rain could enter the soil. The water shed from this screen was collected by gutters and run into a tank in the ground from which it could be pumped into a higher tank and used to irrigate the second sub-plot. The third sub-plot represented unmodified soil water conditions. In the centre of each of these sub-plots a platform was built to facilitate work in the canopy. There were 30—40 trees on each sub-plot, and observations were made on eight central ones adjacent to each platform.

Methods.

Transpiration.

This was determined by measuring the loss in weight of detached branches, or large parts of branches, in 1957, and of detached leaves in 1958, during the ten minutes immediately following severance from the tree.. Between weighings the detached parts were hung in the part of the canopy from which they had been taken. By experiments with three-year-old plants which

could be weighed intact in pots, it was first established that the transpiration of detached branches in the ten minutes following cutting was about twelve percent less than that of undamaged plants; during the same period the transpiration of detached leaves showed, on average, little reduction.

The procedure for measuring the transpiration of the plantation in 1957 was as follows. Determinations were made on successive branch whorls from the top to the base of the canopy of randomly chosen trees, and were repeated at intervals of two hours throughout the day each time on different trees. Thus both positional and diurnal variation was fully sampled. The branches were taken back to the laboratory, cut up and oven-dried, and the foliage removed and weighed. The transpiration rates could then be expressed relative to unit dry weight of foliage, and at the same time estimates were obtained of the weight of foliage per branch in each branch whorl. The numbers of branches per whorl were established by counts on one hundred randomly chosen trees, and an estimate also made of the number of trees per unit area. By suitably combining these observations the depth of water transpired in twenty-four hours could be calculated, and the procedure was repeated at intervals of about two weeks in summer and four weeks in winter. To obtain unbiassed estimates it is necessary to carefully plan the system of combining the various factors, and also to exclude personal choice by using random numbers to select both the trees and the branches to be sampled.

In 1958, when a comparison had to be made between the three differentially treated sub-plots, transpiration was measured on detached needles both for convenience and because the sub-plots were too small for branch samples to be taken. Samples were so chosen that different needle ages and levels of the canopy were adequately and randomly sampled on each sub-plot. The transpiration rates were combined with observations on weights of foliage in the canopy of the area surrounding the sub-plots, but in this case it must be emphasized that although the weights of foliage were obtained by random sampling, the transpiration rates were obtained from sub-plots which, though apparently representative, were nevertheless arbitrarily chosen.

Interception by the canopy.

The rain falling on the plantation was gauged in two clearings. The readings of these gauges agreed satisfactorily with one another and with a standard rain gauging station about 1 Km. distant. The rain reaching the forest floor was measured by twelve rain gauges randomly placed within the area and frequently moved and by ten special gauges which encircled the trunks of randomly chosen trees and collected the water running down them. These were rigorously tested to ensure that they neither leaked nor overflowed.

Evaporation from the soil surface.

Eight randomly placed metal boxes of area 600 cm.^{2} and depth 12 cm. were filled with surface humus and needle litter, disturbed as little as possible. Evaporation of water intercepted by these surface layers could be estimated either from the difference between the rain reaching the forest floor and the water draining from the boxes into receiving vessels, or by the loss in weight on selected days.

Estimating evaporation from soil moisture tension measurements.

Assuming that drainage or capillary rise are negligible in periods when the soil is drier than field capacity, then during such periods evaporation may be estimated from the sum of the rainfall and the change in soil moisture content. Furthermore, in a summer period between the last occasion on which field capacity obtains and the first on which it is re-established, i. e. between two occasions with essentially the same soil moisture content, evaporation and rainfall are equal. This method was suggested by Penman's (1949) study of evaporation in fields; he used observations on whether or not the drains were running as an indication of whether the soil moisture was above or below field capacity. In the present study tensiometers and electrical resistance blocks, inserted at various depths to a maximum of 120 cm. in 1957 and 240 cm. in 1958, were used as indicators of soil moisture conditions. From the readings of the mercury manometers on the tensiometers, soil water potentials relative to the soil surface were calculated. In April and May while the water table fell from 60 cm. to 180 cm. depth, the potential gradient indicated drainage during rainy periods and capillary rise during dry. In the beginning of June the upper 60 cm. of the soil began to dry rapidly. Although this created a potential gradient conducive to capillary rise the tensions were such as would reduce capillary permeability to a negligible level and the sudden steepening of the gradient may in fact be taken to indicate the cessation of capillary rise. After this time, summer rains penetrated only a few dm. into the soil and it was not until the end of December in 1957 and mid-November in 1958 (a wetter year) that low tension conditions were re-established throughout the rooting zone. The water-table which had continued to fall throughout the summer and had reached a depth of 4—5 m., then began to rise again.

On this almost level site no evidence of surface or sub-surface run-off was seen until the water-table had risen to about 40 cm. depth in January and February.

Estimating evaporation from changes in soil water storage.

In 1957, four pits of 120 cm. depth were dug at the end of June and the water content of the profile estimated from twelve samples of known volume (300 $cm.^3$) from each pit. The sampling was repeated at the end of September and the change in water storage calculated. The depth of the pits was a little less than the full rooting depth, but a subsidiary investigation indicated that only about 1.5 cm. water had been removed from the horizon 120—180 cm., and none from the soil below 180 cm.

Results.

Transpiration and Solar Radiation.

Figure 1 shows the relation between evaporation in the plantation and radiation measured with a Robitzsch actinometer at a site about 10 Km. distant, on sample days distributed through 1957 and 58. Excluding a few days (notably May 16, 1958) the two quantities fluctuate together fairly closely, and consequently the evaporation per day has been multiplied by the ratio of the total radiation in the period from which the day was a sample to the radiation on the particular day, in order to estimate the evaporation of the period from that of the sample day.

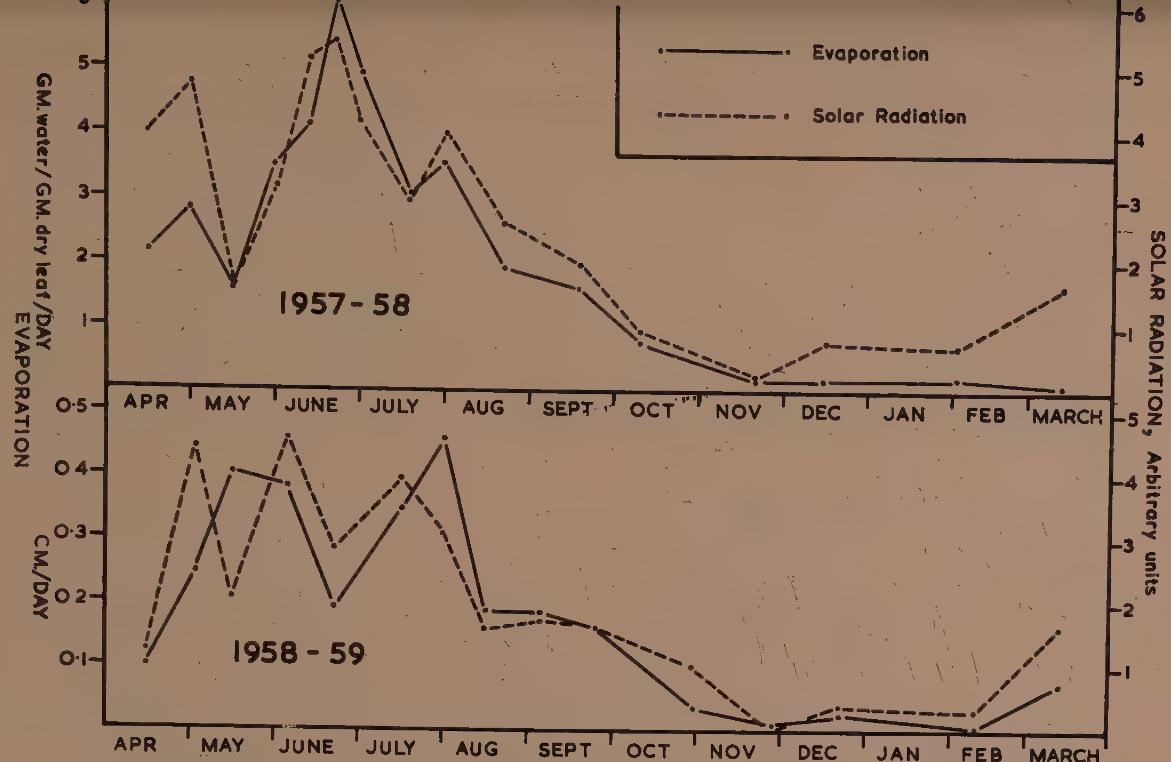

Fig. 1 Evaporation from a pine plantation and solar radiation on sample days through two years.

The results for 1957-58 are shown as loss of wt. per unit wt. of foliage rather than as cm. evaporation because the error of determining the weight of foliage per unit area of plantation on any one sampling occasion tends to mask the relation between cm. evaporation and radiation. This does not apply to the results for 1958-59 when a different method was used to determine the weight of foliage.

Comparison of Methods.

Estimates of evaporation obtained by different methods are compared for the appropriate periods in the first six lines of Table 1.

TABLE 1

Evaporation in a pine plantation estimated by various methods and compared with the potential transpiration of grass.

Period	*Method (Pines)*	*Evaporation, cm.*			Pines: Grass
		Pines	*Standard Error*	*Grass* (potential)	
26/ 6/57—26/ 9/57	Soil sampling	23.6	2.7	21.0	1.12
	Direct (5 sample days)	27,7	1.9		1.32
1/ 6/57— 3/11/57	Tensiometers	41.3	2.2	34.1	1.21
	Direct (9 sample days)	42.4	3.0		1.24
16/ 6/58—14/10/58	Tensiometers	34.4	1.4	24.9	1.38
	Direct (6 sample days)	34.6	—		1.39
1/ 4/57—30/ 9/57	Direct (11 sample days)	53.0	4.7	45.8	1.15
1/10/57—31/ 3/58	Direct (5 sample days)	5.8	—	7.2	0.80
1/ 4/58—30/ 9/58	Direct (10 sample days)	54.6	—	40.2	1.36
1/10/58—31/ 3/59	Direct (5 sample days)	5.5	—	5.8	0.95

The agreement between the methods seems very satisfactory. The very close agreement between the two methods used in 1948 may, however, be fortuitous since transpiration was not determined at random positions but on chosen representative sub-plots.

The dependence of evaporation on weather conditions.

No attempt has yet been made to determine the separate effect of any climatic factors other than solar radiation since no meteorological observations have been made on the site. But comparisons have been made with an estimate of the potential transpiration of grass, supplied by the Meteorological Office and calculated by Penman's (1948) method from observations at South Farnborough, about 12 Km. distant. The comparisons are shown in the last column of Table 1. In the bottom four lines of the table is a summary of evaporation in the two summers and two winters through which observations have been made. During the summer months evaporation exceeded Penman's estimate for grass by 15 % in 1957 and 36 % in 1958. A comparison for separate months is shown in Figure 2 where it will be seen that the two estimates are fairly closely related throughout the year, and that in 1958 the largest excesses over Penman's estimate tend to occur on days when interception was important. This was especially marked on May 16th, when about 0.25 cm. was intercepted from a storm of 0.85 cm. in the night and had completely disappeared by 10.00 a. m.

Since Penman's estimate was obtained from a meteorological station some distance away, the precision of the comparison is uncertain, but it may be noted that the plantation was neither unduly sheltered nor exposed.

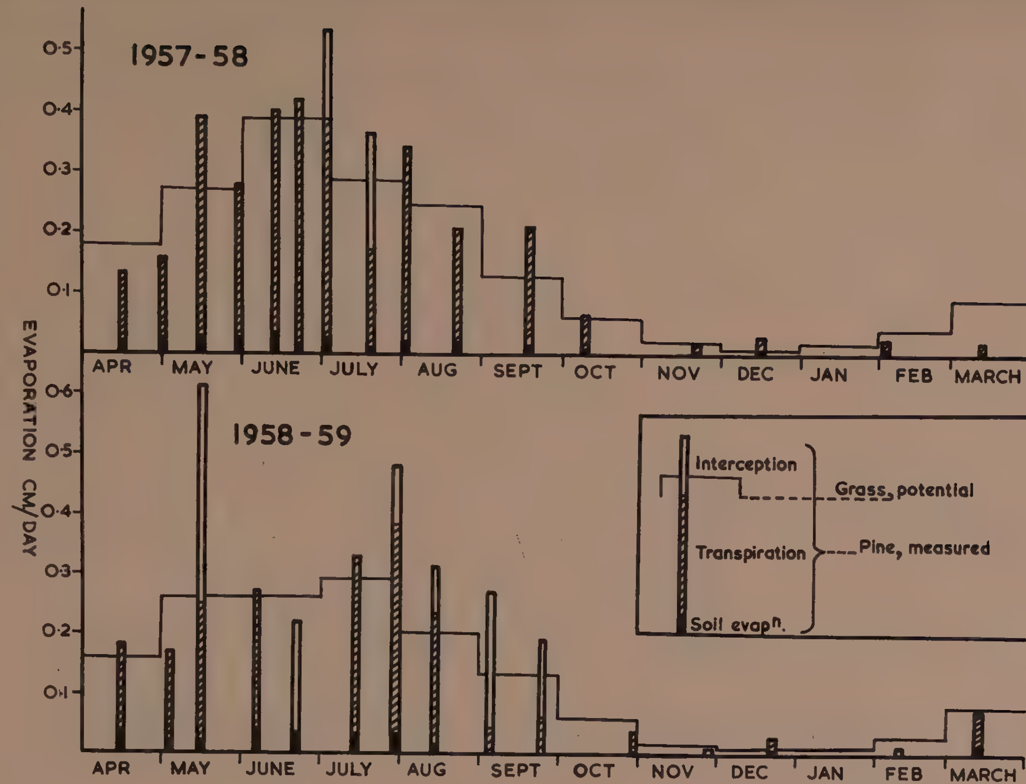

Fig. 2 Evaporation from a pine plantation compared with Penman's estimate of the potential transpiration of grass. Values for pine (Apr.—Sept.) adjusted for radiation on the sample days as explained in text.

Interception.

A summary of observations on interception is given in Table 2.

TABLE 2

Rainfall, Throughfall, Trunk-flow, and Interception, cm.

Period	Rainfall	Through-fall	Trunk flow	Inter-ception	I., % rain	I. per rain day
Apr.—Sept., 1957	30.2	18.6	3.5	8.1	27	0.14
Oct. 57—Mar. 58	36.0	19.5	6.3	10.2	28	0.17
Apr.—Sept., 1958	36.7	19.7	4.0	13.0	35	0.18
Oct. 58—Febr. 59	27.3	14.5	4.8	8.0	29	0.17

Since it was not practicable to visit the site and empty the gauges more than twice a week, no analysis can be made of the interception from storms of different size. The interception per rain day is found to be fairly constant throughout the year, but since a day classed as rainy may have received as little as 0.05 cm., the result is affected by the fact that on many such days rain was insufficient to saturate the surfaces of foliage and bark. On certain occasions in summer the interception from a single day's heavy rain has been distinguished and found to lie between 0.23 and 0.35 cm.

The interception per rain day in winter considerably exceeds both the observed daily transpiration rates and Penman's estimate, which average 0.03—0.04 cm. per day. This might well occur if the rain intercepted on a particular day took several days to evaporate. But whenever it has been possible to observe the disappearance of intercepted water in winter, it has always been found to occur within a day. In addition, the interception per rain day has been calculated for a number of periods in winter when rain has fallen on five or six consecutive days, thus excluding the possibility of one day's interception being evaporated over several days. The average interception in these periods was 0.19 cm. per day. It should be noted that the daily rates of evaporation in winter shown in Figure 2 are therefore biassed by the fact that the few sampling days included none in which interception occurred.

The large discrepancy in winter between the rates of disappearance of intercepted water and of transpiration has led to an examination firstly of the errors of gauging and secondly of the possibility that an appreciable part of the interception is absorbed by the trees rather than evaporated from their surfaces. Space does not allow a lengthy discussion but the following points may be made.

The standard error of both throughfall and trunk-flow is about 0.02 cm./day, and of their combined amounts 0.03 cm./day. Although the trunk-flow gauges were placed on randomly selected trees, it is possible that by chance these trees were far from representative. However, it can be calculated that the apparent interception per rain day would not be reduced to say 0.05 cm./day (a value more consistent with the observed winter transpiration rates) unless the estimate of trunk-flow represented only 45 % of the true value, a chance of very low probability.

Direct experiment on the weights of water retained on the surface of unit weight of foliage shows that this is equivalent in the plantation to 0.1 cm. rainfall, and the water which can be retained by bare branches and the fissured bark of the trunk might account for a further 0.03—0.05 cm. The total of 0.13—0.15 cm. is appreciably less than the figure of 0.19 cm. obtained by gauging but still far exceeds the transpiration rate.

Detached needles hardly absorb any water through their cuticle when immersed for twenty-four hours with only the cut end protruding, and this has also been found true of shoots immersed in water while still attached to the tree.

On numerous occasions comparisons have been made between the loss in weight of needles retaining intercepted rain and similar ones which have been wiped dry, or alternatively, between needles or branches artificially sprayed and others with dry surfaces, and it has invariably been found that the wet needles lose weight at anything from two to five times the rate of dry needles.

Although further quantitative work needs to be done in the plantation there seems no doubt that the evaporation of intercepted water proceeds much more rapidly than transpiration. This is most noticeable in winter but evidence of it is frequent in summer, e. g. the rapid disappearance on May 16th, 1958, of water intercepted at night, referred to above.

Effects of drying soil.

In comparing the observed evaporation from the pine plantation with the potential evaporation from grass, the question arises whether the plantation transpired at its full potential rate throughout the summer or whether its transpiration was at any time restricted by the reduction of soil moisture. In experiments with young plants of *P. sylvestris* growing in pots, Rutter and Sands (1958) had found that transpiration was progressively restricted as the soil dried below field capacity. At the same time there was a steady rise in leaf water deficit and the stomata closed progressively earlier in the day.

Soil water deficits have been calculated for the plantation from the difference between rainfall and evaporation in summer. In 1957 the soil water deficit rose to 10 cm. by the end of June (a dry month) and reached a maximum of 16 cm. in mid September. It is clearly not justifiable to compare the transpiration rates in different soil conditions when these also occur at different times of the year, but the leaf water deficit, which when measured at dawn is relatively insensitive to atmospheric conditions, showed no increase through the summer but remained at a level similar to that normally shown by plants in freely watered conditions, which suggested that the trees had no difficulty in obtaining sufficient water from the soil.

In 1958 comparisons were made at intervals of two to three weeks between the three sub-plots with different soil moisture conditions. Unfortunately for the experiment it was a very wet summer. Evaporation was lower than usual and the result of frequent rains was that the foliage was often wet and consequently not transpiring, and this retarded the development of the soil water deficit beneath the cover on the dry plot. Nevertheless, the calculated deficit attained 18 cm. at the end of August and nearly 20 cm. at the end of September, whereas on the irrigated plot it never exceeded a few cm., and on the normal plot it reached a maximum of 9 cm. at the beginning of August and then declined gradually. These contrasted conditions had no appreciable effect on either leaf water deficit or transpiration. The comparison is being continued in 1959.

Further Work.

The main extensions of the work which are being made in 1959 are firstly the collection of comprehensive meteorological data on the site, and secondly comparisons with a plantation of the same age and density but on a sandy soil with very deep watertable, and also with a grassy heath.

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MEASUREMENT AND INTERPRETATION OF INTERCEPTION OF PRECIPITATION BY FOREST STANDS

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SUMMARY

Daily measurements of throughfall under Lawson cypress during the summer and autumn of 1958 gave interception values (expressed in terms of rainfall in the open) ranging from zero to almost 100 per cent. with a mean, over the whole period, of 12 per cent. Because of variations with location under the crown, with the nature of the rainfall and with other environmental factors, it is essential to adopt a statistical approach and to analyse the data in terms of these variables if a valid estimate of interception by a forest stand is to be obtained. Stem flow was generally of the order of 1 per cent. or below and, even during fog, rarely amounted to more than 5 per cent. of the total throughfall. Because ofthe influence of the stand itself on precipitation, it may be more logical to express interception in terms of rainfall incident on the canopy rather than in the open at ground level.

The significance of intercepted precipitation in the overall water balance of a forest site is discussed in relation to the probable reduction in transpiration following wetting of the foliage.

RÉSUMÉ

Des mesures journalières des quantités d'eau passant par la cime des *Chamaecyparis lawsoniana* pendant l'été et l'automne de 1958 donnaient des valeurs d'interception (basées sur les quantités d'eau recueillies à découvert) allant de 0 à presque 100 %, avec une valeur moyenne de 12 % pour la durée entière de l'expérience. A cause des variations dans les valeurs se rapportant à la position sous la cime, le caractère de la pluie et d'autres facteurs du milieu, il est nécessaire d'employer des méthodes statistiques et d'analyser les données selon ces variables si on veut arriver à une évaluation valable de l'interception des précipitations par les peuplements forestiers. Les quantités d'eau s'écoulant par le fût étaient en général de l'ordre de 1 % ou moins, et même par brouillard atteignaient rarement un chiffre au-dessus de 5 % de la quantité totale passant par les cimes. Vu l'influence du peuplement lui-même sur les précipitations, il est peut-être plus logique d'exprimer les valeurs pour l'interception en termes des quantités qui tombent sur la voûte foliacée, au lieu de celles recueillies à découvert au niveau du sol. On discute le rôle des précipitations interceptées dans le bilan d'eau total d'une station forestière par rapport à une réduction probable de la transpiration conséquente de l'humidification du feuillage.

The interception of precipitation by tree crowns is perhaps the most readily appreciated component of the hydrological cycle of the forest and probably largely because of the apparent simplicity of its measurement and interpretation, apart from its generally recognized importance in the cycle, it has received a considerable amount of attention. In his excellent and comprehensive review, Delfs (1958) quotes well over 100 references covering varying aspects of the phenomenon. Against the background of these intensive and extensive studies it might be thought that, except to fill in certain gaps in our empirical knowledge, little would be gained by a further study of this phenomenon. Yet a critical survey of the work that has been published and some thought as to the significance of the findings suggests that there is still considerable room for improvement in the techniques of

measurement and perhaps the need for further reflection on matters of interpretation.

Precipitation

Interception is capable of different definitions according to whether or not the influence of the stand itself on precipitation is taken into account. In most cases (cf. Delfs, 1958) interception has been defined and measured as the difference between the precipitation reaching the forest floor (including stem flow) and that in the open, either in forest openings or on open ground adjacent to the forest. This definition is consistent with the view that over an area with a uniform precipitation, the only difference is that due to interception by the canopy, allowing of course for stem flow. But it can be argued that since the forest itself, by virtue of its influence on air movement (turbulence), influences the actual precipitation over the area it occupies (there are also marginal effects), true interception can only be defined in terms of precipitation incident on the canopy. It is well known that this may be very different from precipitation in the open at ground level, especially if one includes snow and ice. Unfortunately few investigations have approached the problem in this way. In one of the most recent attempts in this direction, Law (1957) records, on the average, a 13 per cent. lower rainfall catch with 'tree top' gauges than in the open at ground level, but the difficulties of a precise interpretation of his findings and the many complications involved in the measurements make it clear that the problem justifies much closer attention than given hitherto.

Throughfall

It is well known that because of the particular morphology of the tree crown, the variation in crown cover within the stand and variations in the size of the component trees, the amount of precipitation reaching the forest floor (by throughfall and stemflow) is not uniformly spatially distributed. Other factors such as variations in the direction of the rain bearing winds, the nature and distribution of the rainfall and the varying climatic conditions during the year will also result in differences in throughfall with time. Snow, ice and fog introduce further complications in a quantitative investigation of the hydrological relations of the forest.

In the case of a single tree in a forest crop, a fairly consistent pattern in the distribution of throughfall is perceptible for most forest species. Figure 1 illustrates the results obtained by the authors for throughfall beneath a single crown of Lawson cypress (22 years old), using 20 standard 5 inch gauges distributed at random. In agreement with most other findings (e. g. Kittredge et al. 1941), throughfall increases with increasing distance from the stem with a tendency, as mentioned already by Delfs, (1958), for the maximum to occur just within the perimeter of the crown (cf. figure 2). Those gauges situated on the side of the prevailing rain bearing wind (in this case south-westerly) are separately indentified in the figure (by circles) and it is evident that their overall catch is higher than that of gauges at similar distances on other sides. Mean monthly throughfall values over the period July to November, 1958, calculated in terms of per cent. rainfall in the open are plotted in figure 2, again as a function of distance from the stem. Although actual values vary from month to month, the general pattern is the same and the use of mean values (allowing of course for the

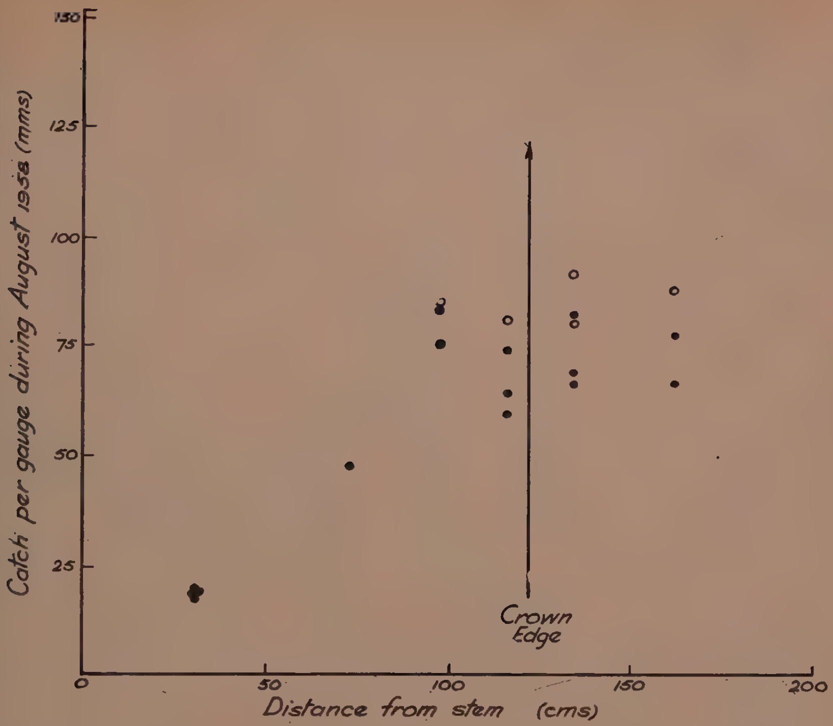

Fig. 1 Throughfall under Lawson cypress as a function of position under the crown.

errors involved) emphasizes the point of maximum throughfall inside the crown perimeter: it is also of interest that at this point, no doubt because of drip, throughfall often exceeds the value of rainfall in the open.

This variation in throughfall from place to place below the stand must be taken into account if a worthwhile estimate of interception is to be made. Too few gauges are liable to give serious errors whilst large numbers are expensive and time consuming. One possible solution lies in stratification whereby the area below the canopy is divided into particular regions representing various average distances from the tree stems so that the catch of gauges located at random in these regions can be weighted for the area represented: this was the method used in obtaining the data presented in figure 2. However, though perhaps suitable for individual trees, this approach may not be very efficient fo the stand as a whole, largely because of the complications in defining the precise strata under an irregular crown cover with openings of different size. An alternative method now being investigated makes use of a random distribution of a number of gauges with a final statistical treatment involving covariance analysis in relation to relative position under the crowns. At the time of writing few results are available but it is hoped that a complete account will be available at a later date. The point of emphasis is that in dealing with an irregular distribution of throughfall, a statistically acceptable layout is essential if any measure of

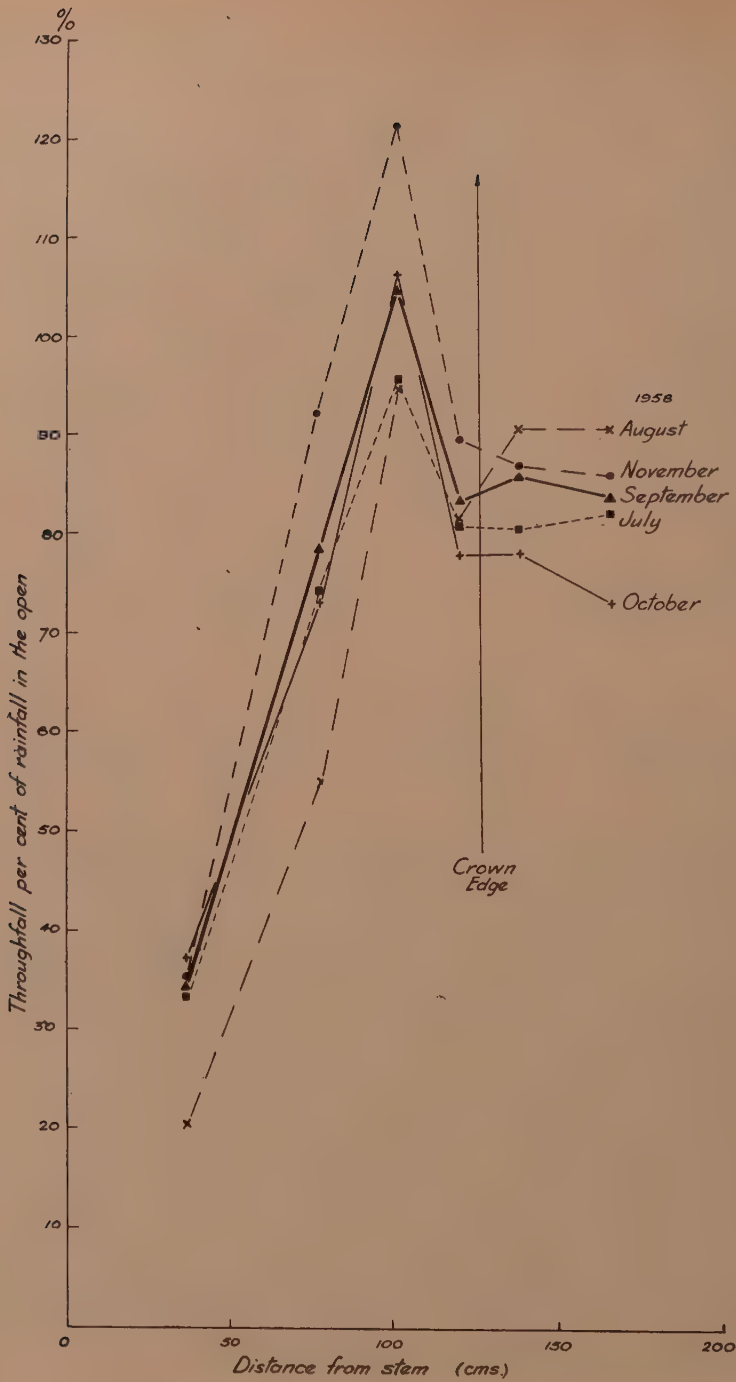

Fig. 2 Mean monthly values for throughfall under Lawson cypress as a function of position under the crown for the period August-November, 1958.

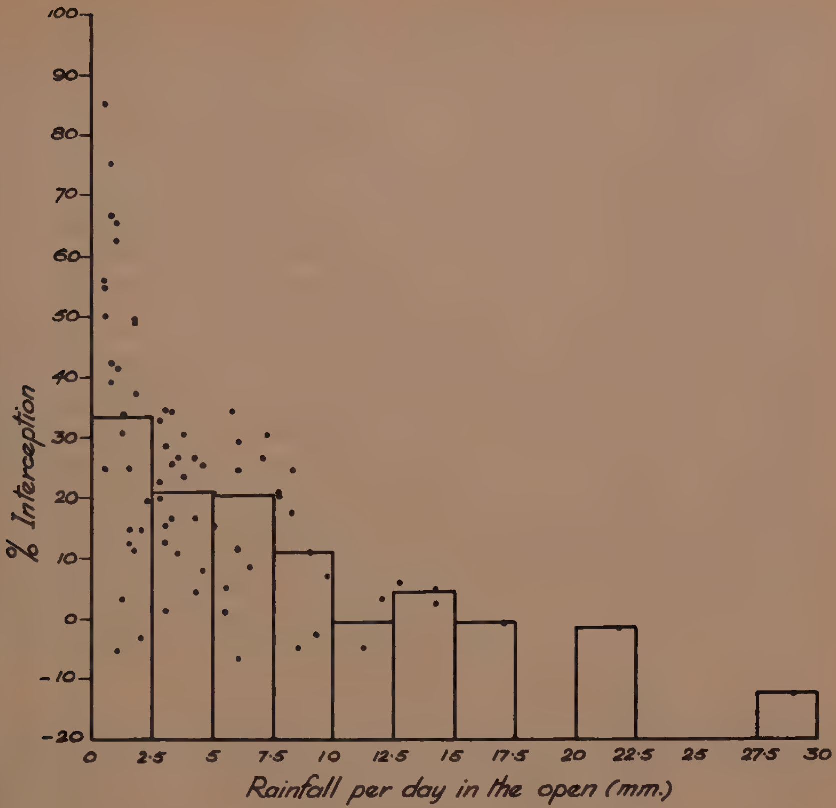

Fig. 3 Daily per cent interception of rainfall by Lawson cypress as a function of rainfall intensity.

the order of the accuracy of the estimate is to be obtained; the value of such knowledge need hardly be emphasized. In a very recent publication on the San Dimas investigations in the U.S.A. (Hamilton & Reimann, 1958), a statistical approach of this kind has led to a reduction in the number of rain gauges over the area from 300 to 21 whilst still maintaining a satisfactory order of accuracy in the estimate of rainfall.

As an alternative to standard gauges, much attention has been paid to the use of troughs of various designs: these certainly possess the advantage of a larger area and hence a better integration of the throughfall, but there is still the need for distribution at various points below the canopy if a truly representative value is to be obtained. Quantitative data on the relative merits of standard gauges and troughs in estimating throughfall would be of considerable interest: investigations on this are being conducted by the authors.

Another most important factor influencing throughfall is the variability in the nature of the precipitation. Excluding the extra complications of snow and ice, the foliage and branches of a particular stand possess a certain

saturation (storage) capacity which, when satisfied, will allow most of the subsequent rainfall to run off without further interception. Starting then from the 'dry' state, interception will approach 100 per cent. (zero throughfall) during the initial wetting period and will then fall to zero or thereabouts as saturation is reached: the exact course will depend on the nature of the rainfall and a certain amount of drip may be expected after the rain has ceased. Subsequently, during dry periods, the water retained by the canopy will evaporate off at a rate depending upon prevailing conditions of temperature, humidity and wind etc.; hence the fate of subsequent precipitation will depend, among other things, on the duration of, and conditions during the dry periods. It is evident therefore that occasional measurements of throughfall are of little value in characterizing interception by a particular stand.

Some of the points mentioned above are illustrated by the data obtained by the authors for Lawson cypress. Figure 3 represents the per cent. interception (in terms of precipitation in the open) for every rainy day during the period July to November 1958, as a function of total rainfall. Despite the scatter, it is evident that interception falls from a value of 80—90 per cent. during days of little rain to zero during very wet days. The histogram representing overall interception values for each 0.1" (2.5 mm.) rainfall class illustrates this very clearly. Much of the scatter of the individual points is undoubtedly due to such factors as the variation in the duration of the rainy (or dry) periods and the varying conditions for evaporation. It would be expected that during colder and more humid periods with little wind, interception would be lower than during drier, warmer periods with infrequent showers. In this respect the data summarized in Table 1, giving the overall monthly interception values during the period July to November 1958, provide some confirmation of these expectations.

Although the total rainfall was fairly evenly distributed over the period, interception during July and August was higher than that during September and October and very much higher than that in November. November was characterized not only by fewer hours of sunshine and lower temperatures but also by a larger number of days of fog, all of which would be expected

TABLE 1

Climate, interception and stemflow in Lawson cypress, Bagley Wood, Oxford (July-November, 1958)

	July	August	September	October	November
Total sunshine (hours)	188	120	122	94	52
Mean T (°C)	16.7	16.7	15.6	11.3	6.6
Total rainfall (mm.)	71.2	84.6	75.2	69.7	80.8
No. of hours of rain	38.4	52.3	38.4	36.4	69.9
No. of days with rain	22	27	17	22	24
No. of days with rain > 0.25 mm. (0.01")	17	21	10	13	12
No. of days of fog	—	—	4	9	13
% Interception	16.7	17.8	11.3	14.4	2.8
Stem flow (mm.)	0.5	trace	0.8	1.8	4.8

to decrease evaporation and probably to increase throughfall by condensation. It is of course not always possible to forecast the order of interception from the meteorological data available (compare, for example, the figures for August and September). The important point is that from day to day and month to month, interception may vary considerably; this means that continuous estimates of throughfall must be made under all possible variations in climatic conditions if a representative value for a given forest cover in a given region is to be obtained. Bearing in mind the previously described need for a large number of gauges to allow for spatial variations, the expense and labour is therefore considerably increased. The installation of recording equipment is an obvious solution, but other approaches are worthy of consideration.

With a limited number of gauges one of the most rational approaches is that initiated by Wilm (1943) in which the gauges are moved to new positions after each storm or, as in Law's (1957) investigations, after a certain quantity of rainfall. In this way, variations in both position under the canopy and nature of the rainfall are covered; however, few attempts have been made to compare the efficiency of the various procedures. In an investigation recently begun by the authors in a stand of c. 20 year Norway spruce, 20 gauges are distributed at random over an area of about $^1/_2$ an acre, each gauge being periodically moved at random to another position; by relating the results, not only to position under the canopy but also to climatic factors it should then be possible, by statistical analysis, to obtain a reasonably representative value for throughfall in this stand. One further advantage of this approach is that the standard error of the estimate is then calculable for any given number of gauges.

Stem flow

Stem flow is influenced by many factors, the nature and age of the species (size and form of crown, nature of branching, type of bark), also the nature of the rainfall and the time of the year; snow introduces a further important source of variation. The numerous investigations on this phenomenon are reviewed in some detail by Delfs (1958). Generally, under similar climatic conditions, stem flow is greater and begins at a lower rainfall in deciduous trees than in conifers. Thus, whereas figures of the order of 5 to 20 per cent. of the rainfall in the open have been quoted for deciduous trees (in a number of cases, these exceed the values for interception), for conifers, the values are usually of the order of 1 to 2 per cent. In deciduous trees, stem flow may occur with a rainfall of as low as 2 to 5 mm.; in conifers, usually a much higher rainfall is necessary, of the order of 5 to 15 mm.

Lawson cypress provides no exception to the general rule for conifers. The data given in Table 1 show that in terms of rainfall in the open, stem flow is generally ofthe order of 1 per cent. or below: only during foggy weather, as in November, does its value approach 5 per cent. Usually no stem flow was recorded with this species until the rainfall in the open exceeded a value of the order of 5—10 mm.

In general, therefore, it would appear that in older coniferous stands, the omission of stem flow measurements would not lead to appreciable errors in the estimation of the amount of water reaching the forest floor. In other cases however, and most certainly with deciduous species, especially during fog and winters with snow, it would be necessary to take stem flow into

account: in such cases, because of variations, even within an even aged stand of the same species, sampling of a number of trees and a statistical analysis of the results are again essential for an unbiassed estimate.

The interpretation of interception

In most publications dealing with this phenomenon, it has been stated, or at least implied, that interception represents a net loss in the water supply th the soil (cf. Law, 1957; Delfs, 1958). However, on purely theoretical grounds, if the energy relations are considered (cf. Penman, 1948), it can be argued that since a given supply of thermal energy will only evaporate a certain quantity of water, then the evaporation of water retained by the foliage must be compensated by a reduction in transpiration and consequently in water uptake by the trees. Unfortunately no measurements appear to have been made as yet on trees, but there is a certain amount of experimental evidence on shrubs and herbs (including grasses) which supports this view. Thus Bernick (1937/8) describes experiments on herbs showing that the early morning wetting of the foliage by dew delays the onset of transpiration for many hours; he quotes this finding as being in agreement with certain earlier observations. Jones (1957), working on excised leaves of *Salvia* also showed that wetting with spray induced earlier stomatal closure and increased conservation of water. More recently, Burgy and Pomeroy (1958) sprayed various herbs and grasses (grown in nutrient solution) with water and found that overall, wetted foliage lost no more water than non-wetted, occasionally in fact, rather less: only where non-transpiring organs were wetted, was there a net interception loss.

It would appear therefore, that the interception of precipitation by forest canopies does not necessarily mean a corresponding loss to the site. Until such measurements have been made on tree crops however, the order of the losses involved cannot be deduced simply from interception data. Experiments are on hand to investigate this problem in more detail.

Conclusions

Interception of precipitation by the canopy is undoubtedly a significant phase in the hydrological cycle of the forest. However, in any particular stand, there are numerous factors which influence the extent of interception both spatially and in time. The examples given for Lawson cypress show, in agreement with previous findings, that throughfall is a function of position under the crown and that it may also vary considerably in time with the nature of the rainfall and the conditions for evaporation. If reliable estimates of interception are to be made therefore, a thorough sampling is essential with respect to both position under the canopy and the range of weather conditions experienced. To achieve this at reasonable expenditure of money and time, some statistical approach is necessary and of the various procedures possible, that involving the random distribution of gauges, moved around the stand at certain intervals of time or rainfall appears to be the most efficient.

Some doubts may be expressed as to the definition of interception in terms of precipitation in the open at ground level since it may be argued that if allowance has to be made for the influence of the stand itself on precipitation, it would be more logical to relate interception to precipitation incident on the canopy. This measurement is by no means a straightforward

one and much work still remains to be done before a satisfactory solution can be expected.

Both on theoretical arguments based on the energy concept and from experiments on shrubs and herbs, it would appear that loss by interception of rainfall reaching the forest floor need not necessarily mean a net loss in water supply: it is very likely that to a certain extent at least, loss by interception is compensated by reduced transpiration. Experiments on tree crops are urgently required to test this point. Although it might be argued that the effect of a canopy in inducing a change in the nature of the precipitation (e. g. size of rain drops, icing, snow retention and stem flow etc.) may be of some importance there can be little doubt that confirmation of the absence of an appreciable net loss to the soil would modify considerably many of the present interpretations of this phenomenon.

It must also be borne in mind that when the question of water losses from a forest cover is being considered in relation to those from other types of vegetation such as grasses or agricultural crops, these also intercept a certain amount of the rainfall; although the ratio of interception loss to transpiration loss may be different from that in the forest, the net loss should, on consideration of the energy consumed in evapo-transpiration, be of a similar order to that for a forest cover; unfortunately, we have as yet, insufficient data as to the influence of factors such as differences in surface roughness, micro-climate etc. to attempt a quantitative assessment of the difference between one type of cover and another.

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ALPINE SNOWFIELDS—THEIR CHARACTERISTICS AND MANAGEMENT POSSIBILITIES

by M. MARTINELLI, Jr. (1)

SUMMARY

Studies have been carried out at elevations of 3,500 to 3,800 m in the Rocky Mountains of Colorado to determine the role of alpine snowfields in maintaining streamflow during the summer months. Density and ablation were measured weekly for four summers. The moisture exchange at the snow surface was measured 2 years by the use of plastic containers.

Weekly ablation varied from 30 to 85 cm of snow. During the summers of 1955 and 1956 it averaged 58 cm of snow per week. Density increased during the summers, reaching a maximum in late July or August. August densities ranged from 0.6 to 0.8 gm/cm^3. About 3.5 m of water per unit area of snow was released from the snowfields during July and August. During a period of humid weather the snow gained moisture through condensation and during a dry windy period the snowfields lost moisture to the air. In both cases, however, the rate of moisture exchange was less than 3 pct of the water equivalent of daily melt.

Proposals are made to sustain summer streamflow by constructing barriers to drift additional snow into natural catchment areas and to regulate the melt rate by the addition of materials to the snow surface.

RÉSUMÉ

Des études ont été faites à des altitudes de 3.500 à 3.800 m dans les Montagnes Rocheuses du Colorado pour déterminer le rôle des champs de neige alpestres sur le maintien des débits pendant les mois d'été. La densité et l'ablation furent mesurées une fois par semaine pendant quatre étés. L'échange d'humidité à la surface de la neige fut mesuré pendant deux années à l'aide de récipients en plastique.

L'ablation hebdomadaire variait de 30 à 85 cm de neige. Pendant les étés de 1955 et de 1956 la moyenne fut de 58 cm de neige par semaine.

La densité augmentait pendant l'été, atteignant un maximum à la fin de juillet-août. Les densités de août étaient comprises entre 0,6 et 0,8 gr/cm^3. Les champs de neige fournirent environ 3,5 m d'eau par unité de leur surface pendant juillet et août. Pendant une période de temps humide, la neige absorbait de l'humidité par condensation tandis qu'elle en perdait (vers l'air) au cours d'une période de vent sec. Dans les deux cas cependant, le taux d'échange d'humidité fut inférieur de 3 % de l'équivalent en eau de la fusion journalière.

Des propositions sont faites pour maintenir les débits d'été en construisant faces naturelles de captage et pour régulariser le taux de fonte de la neige en ajoutant certaines substances à la surface de neige.

INTRODUCTION

Above timberline in the Rocky Mountains of the western United States, snow depths are highly variable. During the winter and spring months, snow is blown from exposed sites into depressions and the more protected spots. As a result, the snowpack in this alpine zone is characterized by bare ridges and pockets of deep snow (8 to 15 m deep) interspersed in the general

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expanse of shallow snow (1 to 2 m deep). The shallow snow disappears during late spring, isolating the pockets of deeper snow. The larger of these snow patches or snowfields have depths of 10 to 12 m and areas of 8 to 10 ha at the end of June. Usually all snow is gone by mid-September; however, when the occasional cool summer follows a winter of heavy snowfall some snow will last all summer in many of the snowfields. Downslope movement of the snow and ice is generally not present in the summer even in the deeper and more persistent snowfields where a firn layer develops. It has been assumed that such late-lying snowfields are an important source of summer stream-flow in Colorado; however, there has never been any direct evidence to support such an assumption.

During the summer of 1955, studies were started in Colorado to gain a better understanding of the importance of late-lying alpine snowfields for summer streamflow and, if warranted, to develop management techniques to increase summer streamflow from these areas. The first step in the study was a survey of the physical characteristics of alpine snowfields. This was followed by studies of the rate of evaporation and condensation at a summer snow surface.

Study areas

The survey of physical characteristics was carried out at five snowfields during the summer of 1955. It was repeated in 1956 at two of the fields and continued in 1957 and 1958 at one field. The moisture exchange study was carried out during the summers of 1957 and 1958. All fields were located along the eastern flank of the Front Range in Colorado (latitude 39°30' to 40°30' N, longitude 105°40' to 105°35' W). Some of the more important features of the snowfields are given in Table 1.

TABLE 1. — *Summary of important features of the snowfields studied.*

Snowfield	Aspect	Elevation	Date of first observation	At time of first observation	
				Max. depth	Area
		Meters		*Meters*	*Hectares*
1	East	3,800	June 23, 1955	5.9	1.323
			July 3, 1956	5.1	0.923
			July 3, 1957	—	1.813
			June 26, 1958	—	1.129
2	South	3,500	July 1, 1955	6.6	3.492
			June 30, 1956	5.1	3.428
3	Northeast	3,700	July 3, 1955	2.4	0.186
4	North	3,600	July 4, 1955	a)6.6	1.542
5	North	3,500	July 19, 1955	a)5.7	1.064

(a) Depth of snow above an ice layer of undetermined thickness.

In general the snowfields had slopes between 12 and 35 pct. However, in a few places slopes up to 85 pct were encountered. Snow surfaces became pitted or rippled at times each summer. Dirt and organic material also appeared on the snow surface late in the summers.

Instrumentation and methods

Density and ablation were measured weekly and weather data were recorded as part of the survey study. Ablation of the snow was measured by a rectangular grid of poles placed in holes drilled in the snow. Paint marks on the poles permitted snow depth to be read at a glance. The difference between successive snow depths gave a measure of vertical ablation. Horizontal shrinkage of the snow was determined from weekly maps of the snowfield.

In addition to the weekly ablation data, the observers also measured ablation during their visits to the fields. These short-term ablation values revealed variations with time of day and weather conditions.

In general, the poles proved to be very satisfactory. However, during periods of sunny weather, sun cups developed around the poles. This made it necessary to lay a short stick on the snow surface beside the stake to determine the elevation of snow surrounding the stake.

Density was measured with the Mount Rose snow sampler at several places on each snowfield every week. Supplemental density measurements were also made after August 22, 1956 from pits using 500 ml cylinders.

Accurate density measurements were difficult with the Mount Rose snow sampler. Seldom could it be forced more than 60 to 70 cm before the core had to be emptied to permit deeper sampling. Repeated entry into the hole forced snow into the tube through the slots. As a result, core length exceeded snow depth by 12 cm for snow depths from 0.5 to 2 m. Therefore, densities computed in the usual manner from snow depth were less accurate than those based on core length. In the few samples where a direct comparison could be made, even the Mount Rose densities based on core length averaged 5.7 pct higher than densities taken in pits nearby. However, for the remainder of this report, all density values not specifically referred to as pit densities will be based on data taken with the Mount Rose sampler and corrected for core length.

Free water content in the top 30 cm of snow was measured by the calorimeter technique described by Bernard and Wilson (1941). Measurements were made between 10h 30m and 15h 30m local time. This technique probably gave only moderate accuracy because of the difficulties of measuring water temperature in the calorimeter under field conditions.

Weather data were taken within 30 m of the July 1 snowline at each field. Wind travel at 1.8 m was measured with a three-cup anemometer. Temperature and humidity were measured with a hygrothermograph mounted 1.2 m above the ground in an instrument shelter.

Results

Weekly ablation varied from 30 to 85 cm of snow. Average ablation for the first two summers was 58 cm of snow per week. Rates during the last two summers were slightly higher. The data given in Table 2 are averages based on weekly readings taken on 10 to 80 stakes at each field.

TABLE 2. — *Average ablation in centimeters of snow per week for several elevations and aspects.*

Month and year		Elevation and aspect				
		3,800 meters East	3,500 meters South	3,500 meters North	3,600 meters North	3,700 meters Northeast
July	1955	55	70	a)73	67	73
	1956	46	61	—	—	—
	1957	49	—	—	—	—
	1958	58	—	—	—	—
August	1955	52	73	61	61	—
	1956	43	64	—	—	—
	1957	43	61	—	—	—
	1958	b)61	—	—	—	—
September	1955	b)43	—	b)46	b)40	—
	1956	b)43	b)58	—	—	—

(a) Ablation was measured for only the last two weeks of the month.
(b) Ablation was measured for only the first two weeks of the month.

Short-term ablation rates varied from a maximum of 1.9 cm/hr to a minimum that was too small to be detected by the methods used. The maximum rate was measured late in the morning of a cloud-free day in late August 1955. The minimum was during an overnight period 2 years later when no measurable ablation took place for a 12-hour period. The summary presented in Table 3 illustrates the diurnal trend of ablation during summer months.

Snow density increased during the summers, reaching a maximum in late July or August and then slowly decreased. In the dense, isothermal snow of the alpine snowfields, densities during July ranged from 0.5 gm/cm^3 to 0.7 gm/cm^3. August densities varied from 0.6 gm/cm^3 to 0.8 gm/cm^3.

Pit densities taken at one field in the summer of 1956 indicated an increase in density with depth. Similar studies at another field the same summer were inconclusive.

TABLE 3. — *Variation in ablation with time of day for a snowfield with a southern exposure at an elevation of 3,500 m for the period August 22—31, 1957. Values are the mean of 4 or 6 days.*

Time of day		No. of days	Average ablation cm/hr
From	Until		
6h 00m	9h 30m	4	0.59
9h 30m	12h 30m	4	0.89
12h 30m	14h 00m	6	0.96
14h 00m	21h 30m	6	0.28
21h 30m	6h 00m	6	0.06

Snow quality determinations showed that the average free-water content in the top 30 cm of snow during the late morning hours of August 1956 varied from 6 pct on an eastern exposure at 3,800 m to 11 pct on a southern exposure at 3,500 m. Free-water content as high as 37 pct was found in the slush that formed just above ice layers.

The rate at which the area of the snowfields decreases seems to vary from field to field. Those in shallow, irregular depressions melt more rapidly than those in deep, steep-sided depressions. However, for a given field, there seems to be a characteristic rate of decrease that remains uniform from year to year. Figure 1 illustrates the decrease in horizontal extent of one of the alpine snowfields for four summers. Notice the uniform rate of decrease for the different years in spite of the large amount of snow in 1957.

An estimate of the water released from the snowfield is given by the product of average ablation times average density, if we neglect consolidation of the snow. Applying this relationship to the weekly values for ablation and density, we estimated that during July and August 3.5 m of water are released per unit area of snow. If we assume a linear decrease in snowfield

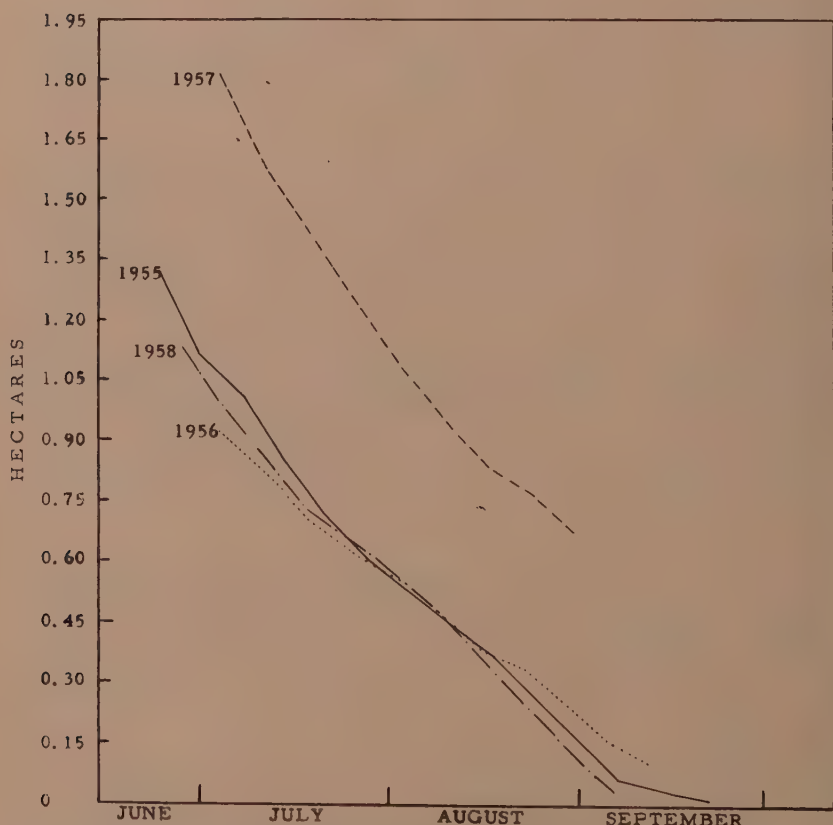

Fig. 1 — Area by dates for a snowfield at an elevation of 3,800 m and an eastern exposure.

area, this would amount to about 5,740 m^3 of water released during the 2-month period, July-August, for each ha of snow present on August 1. This may or may not be a good estimate of the water available for streamflow depending on the importance of evaporation and condensation at the snow surface. These in turn are dependent upon weather conditions.

Weather factors

The average values for the daily mean, daily maximum, and daily minimum temperatures for July and August on an eastern exposure at 3,800 m were:

Mean of daily means	5° to 8° C
Mean of daily maxima	10° to 13° C
Mean of daily minima	1° to 3° C

Only 12 times during the summers of 1955-1958 did the July and August temperature drop below 0° C at this site; however, one of these times it stayed below freezing for 14 consecutive hours. Another site 300 m lower and on a southern exposure had temperatures consistently 2° to 3° C higher than those given in the above tabulation.

Precipitation usually fell as rain or graupel or as a mixture. Total July and August precipitation at 3,800 m on an eastern exposure is given below:

1955	30 cm	1957	25 cm
1956	12 cm	1958	10 cm

Precipitation usually fell during thunderstorms of short duration. Only once for the entire period of record did total precipitation per storm exceed 2.5 cm. Thirty-minute intensities rarely exceeded 2.5 cm/hr.

Winds 1.8 m above the ground averaged 1.8 to 3.6 m/s based on weekly wind travel. At the only field where short-term wind speeds could be determined, maximum velocity during the summer of 1956 was 14 m/s. These relatively light winds appear contradictory to the general impression of the alpine. However, the presence of snowfields indicates local wind shadows. Undoubtedly wind speeds on the exposed ridges and summits, or at the peak of short gusts, were much greater than the average velocity measured near the snowfields.

Atmospheric moisture exchange

Since atmospheric moisture exchange has a direct bearing on the amount of water available for streamflow, it was considered necessary to determine at least the relative order of magnitude of this factor. For the summers of 1955 and 1956 local weather data and Sverdrup's mass transfer equation (Light, 1941) were used to compute the rate of moisture exchange at the snow surface. These estimates indicated a small net loss of moisture from the snow surface due to evaporation. However, the computed moisture exchange data were considered inadequate primarily because of the lack of precision in the humidity measurements.

The next two summers more direct measurements of the moisture exchange between the atmosphere and an alpine snow surface were made. Plastic containers were used to expose known amounts of snow to the atmosphere. Periodic measurements revealed the gain or loss of mass due to con-

densation or evaporation. Moisture exchange was found to have a diurnal trend with condensation usually taking place at night, evaporation in the morning, and either evaporation or condensation in the afternoon, depending on weather conditions. Maximum exchange rates as measured in plastic containers 41 cm in diameter were —0.0229 cm/hr and +0.0076 cm/hr. The average rates of moisture exchange were +0.0660 cm per day for a period of humid weather and —0.0686 cm per day for a dry windy period. These represent a gain of 6.67 m^3 of water per ha of snow per day and a loss of 6.80 m^3/ha of snow per day respectively. It should be emphasized, however, that atmospheric moisture exchange rates averaged between 2 and 3 pct of the water equivalent of the daily melt. Hence, for most practical hydrologic problems, atmospheric moisture exchange at the snow surface in summer can be ignored.

Management possibilities

These studies have suggested that alpine areas could be managed to increase summer streamflow by increasing the amount of snow in the snowfields at the beginning of summer and by regulating the rate of melt. The most obvious technique for regulating the melt rate is the application of materials to the snow surface to change the amount of solar energy available to the snow. Fairly thick (5—8 cm) layers of such things as sawdust or soil insulate the snow and slow melt. Thin layers of black materials such as coal dust or carbon black speed melt by increasing the amount of solar energy absorbed. Computations based on local value for solar radiation show that the increase in melt at a darkened summer snow surface in the alpine could be as much as 35 to 45 pct. This is assuming the material changed the albedo of the snow from a normal summer value of about 0.5 to 0.1 for the blackened snow. Very limited preliminary tests in Colorado during the summer of 1956 showed that a thin layer of dark material increased melt by about 9 pct. However, it is felt that more efficient use of the black material would give greater melting. As part of the same tests, a 5-cm layer of sawdust decreased the melt rate of undisturbed snow by about 50 pct.

Another more promising management technique is the use of artificial barriers to increase the depth and extent of alpine snowfields. Observations and preliminary studies have shown the size and depth of the snowfields to be related to the size, shape, and orientation of the barrier behind which they accumulate. In many alpine areas natural catchments are filled early in the accumulation period. Once the natural barriers are saturated, the wind-borne snow of later storms is swept across the gently undulating snow surface to be deposited in the timber farther down the mountain. The melt water from such snow enters the streams in the spring when the streams are already full and must be stored in reservoirs for use later in the summer.

Artificial barriers could be constructed at site where drifting occurs naturally and thus induce additional drifting. Such barriers should be designed and located to increase the size of drifts that already persist most of the summer or to increase the depth of snowdrifts that normally melt out by mid-summer. This would increase both the amount and the duration of melt water released for summer streamflow. The storage of water in the form of high altitude snowfields rather than low altitude reservoirs will also mean a net reduction in evaporation losses.

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THE MOISTURE FLOW TECHNIQUE FOR DETERMINING THE WATER-BALANCE

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SUMMARY

The water-balance of an area with a watertable at a moderate depth may be deduced from the depth of the water level in the soil, the level in the ditches, the rainfall and the potential evaporation. The pressure gradient of the groundwater stream is a parameter for the sub-terranean run-off. The change in the water level due to rainfall or evaporation is a measure for the storage of water. The real evaporation is a function of potential evaporation, rainfall and capillary supply. The solution of the relation between the known parameters and the magnitude of run-off, storage or evaporation is of the nature of the solution of unknowns out of a number of equations. The equations, however, are still to be found. As long as one is not certain as to the precise type of the equations, the solution is to be found graphically.

The results of a lysimeter research in the Rottegatspolder are used to prove the correctness of the solution obtained. The result seems to be satisfactory. The equations, which may express the different terms of the water-balance are becoming better known. The run-off can be sufficiently described by the steady flow formula, used for land-drainage. The storage shows a marked parallelity with the formula for steady capillary flow. Only the pF-curve does, in comparison with the Rottegatspolder results, not sufficiently allow for the larger cracks in the soil profile, due to difficulties in sampling. The relation between the real and the potential evaporation is still too little known to be expressed in a third formula. A numerical solution of a functional nature is therefore not yet possible, but the graphical solution gives already a good insight in the nature of the water-balance.

The aim of this investigation was to devise a field method, which may allow for the multiple variations in the hydrology of the field in question. The technique requires only a limited cost of installations in the field or in days of field-work. The real difficulties are to be solved at the desk.

RÉSUMÉ

Le bilan d'eau d'une région où la nappe d'eau souterraine est de profondeur modérée peut être déduit de la profondeur du niveau des eaux dans le sol, le niveau dans les fossés, les précipitations et l'évaporation potentielle. Le gradient de pression du courant des eaux souterraines est un paramètre de l'écoulement souterrain. La modification du niveau des eaux souterraines causée par les pluies ou par l'evaporation constitue une mesure de la rétention d'eau. L'évaporation réelle est une fonction de l'évaporation potentielle, des pluies et de l'apport capillaire. La solution du rapport entre les paramètres connus et l'importance de l'écoulement, de la rétention ou de l'évaporation est de la nature du calcul d'inconnues comprises dans un certain nombre d'équations. Mais il s'agit de trouver ces équations. Tant que l'on n'aura pas de certitude en ce qui concerne le type exact des équations, la solution devra être trouvée par la voie graphique.

Les résultats des recherches lysimétriques dans le « Rottegatspolder » sont utilisés afin de démontrer l'exactitude de la solution obtenue. Le résultat semble être satisfaisant. Les trois équations pouvant exprimer les différents termes du bilan d'eau commencent à être mieux connues. L'écoulement se décrit convenablement par la formule de l'écoulement de filtration permanente, utilisée pour le drainage des champs. La rétention présente un parallélisme remarquable avec la formule de l'écoulement capillaire permanente. Seul le tracé du pF, comparé aux résultats obtenus dans le Rottegatspolder,

ne rend pas suffisamment compte des brisures importantes des profils du sol, ce qui doit être attribué aux difficultés d'échantillonnage. Le rapport entre l'évaporation réelle et l'évaporation potentielle est encore trop peu connu pour être exprimé en une troisième formule. Aussi n'est-il pas possible de donner à l'heure actuelle une solution numérique de caractère fonctionnel, mais la solution graphique donne déjà bien idée de la nature du bilan d'eau.

Le but de cette étude était d'élaborer une méthode de plein champ rendant compte des multiples variations de l'hydrologie du champ considéré. La technique comporte des frais modérés d'installations sur le terrain ou de journées de travail extérieur. Les véritables difficultés restent à résoudre dans le cabinet de travail.

The application of the technique to field conditions

The water-balance of any given area is determined by the many varying properties of soil and crop. Sub-surface runoff depends on the permeability of the sub-soil and thickness of the permeable layer. Storage of water in the soil is determined by the distribution and magnitude of the pore spaces. Capillary movement is a function of the same pore-space distribution and of the capillary conductivity. Evaporation is determined by a number of properties such as radiation, windspeed, leaf area, soil moisture tension, and so on.

If one ponders on what the lysimeter—the commonest way of studying the water-balance—can reveal about the water-balance of an area with varying hydrological properties, it will be clear that this approach is of limited applicability. The conditions in the soil block of a lysimeter are unnatural, the variation in conditions very limited. The extrapolation of lysimeter findings to the varying conditions in the field is therefore restricted.

It also seems very uncertain as to whether the lysimeter technique, based on the measurement of volume or weight, may ever be adapted for use on large areas. Moisture sampling is very time-consuming, electric devices for moisture determination with resistance blocks are of limited reliability and are further hampered by the irregularity of the moisture distribution in the soil. It is understandable therefore that researchers seek other ways for the investigation of the water-balance.

The fundamentals of the moisture flow technique

The moisture stream, flowing from the atmosphere through the soil to a drainage canal or from the soil into the atmosphere may be depicted by a flow diagram. The water passes through four distinct sections of the flow path, the saturated zone in the soil, the unsaturated zone, the plant and the air. The water level in a drainage canal represents the potential at a lower end of the flow path, the evaporating capacity of the atmosphere represents the potential at the upper end *). If the flow is of a steady nature—with only the quantity of flow and the pressure-head as variable quantities—then, for each separate point along the path, one would require only one single determination of pressure or flow.

*) The evaporating capacity of the atmosphere is strictly speaking no potential, but a potential multiplied with a number of constants. It may however be used in the same sense as a potential in this investigation into the number of required constants.

The amount of flow is a function of the pressure gradient. For every section it can be expressed as

$$Q = k\, f\left(\frac{dh}{dl}\right) F$$

where, Q = constant quantity of flow
F = cross-sectional area through which water flows
dh = difference in pressure head over a short length dl of the flow path
f = arbitrary function
k = hydraulic conductivity

The value of Q for a certain section is the same for the next section if no storage takes place. The relation may be re-written as:

$$\frac{f\,(d\,l_1)}{F_1}\; Q = k_1 f_1 (d\,h_1) = k_2 f_2 (d\,h_2) \frac{f_1 (d\,l_1)}{f_2 (d\,l_2)} \frac{F_2}{F_1} = k_3 f_3\; d\,h_3\; \frac{f_1 (d\,l_1)\, F_3}{f_3 (d\,l_3)\, F_1} = \ldots$$

The subscripts indicate different sections of the flow path.

Because $\frac{f_1 (d\,l_1)}{f_2 (d\,l_2)} = c_2;\ \frac{f_1 (d\,l_1)}{f_3 (d\,l_3)} = c_3 \ldots$ and $\frac{F_2}{F_1} = d_2;\ \frac{F_3}{F_1} = d_3 \ldots$

with c and d constant, it follows that

$$k_1 f_1 (d\,h_1) = c_2\, d_2\, k_2 f_2 (d\,h_2) = c_3\, d_3\, k_3 f_3 (d\,h_3) = \ldots C = \text{constant}$$

If C is known, then a value for k determines the value of f (dh). If f (dh) is known—and this means that h at the beginning and end of each section should be determined—then the k-values can be calculated.

If the course of the streamflow is divided into the sections corresponding to the atmosphere, the plant, the capillary zone and the groundwater zone, then, for these four sections, the determination of five potentials and one absolute quantity of the flow will suffice. There are only six independent variables.

The stream-flow function may be complicated and may require a number of physical soil constants for its solution. However, these are properties that generally do not change appreciably with time: they may be determined beforehand and only once. Knowledge of these soil constants is a first requirement; a second is that the stream-flow function should be known. In the solution to be discussed later, there is sufficient opportunity to determine functions and constants and to check them on constancy of value.

If the flow is of a non-steady type the problem does not change greatly, but it will be clear that extra information is required. In order to get an absolute measure of storage capacity it is necessary to compare two quantities of water with the two corresponding levels of storage. It may be expected that for a larger number of corresponding quantities of water and levels of storage the storage capacity will show a simple relation with these two values. This furnishes a control.

An other control which ensures that the value found for the storage capacity is correct, arises from the periodic nature of the changes in the water-balance. If the sum of the quantities of storage and depletion over some length of time—for instance a year—becomes zero, then the levels of storage must at the beginning and end of this length of time be the same.

The variations in storage are in most cases related to the same potentials which govern the stream-flow. For instance, if the groundwater table is nearer to the soil surface, the amount of stored water is increased. The pressure gradient and therefore the amount of flow may remain the same

as before this increase in storage. Together the water levels in the soil and in the ditch not only give an idea of the amount of flow, but also of the amount of stored water. In this storage-study therefore, it is not necessary to determine new variables. However, it will be necessary to determine special storage constants, for instance the storage capacity of the soil. If storage is also included in the study, it is not necessary to determine more variables, but only to measure more constants which may describe the conditions of the flow.

Five potentials therefore not only suffice for the establishment of the quantities of flow, but also to determine the changes in storage. These five potentials should be measured at five points along the path of the stream-flow at the beginning and end of each section. If potentials are measured at more than this minimum number of points, then there is a possibility for adjustment of errors of determination. Also one may select the points of measurement in such a way that the determinations of quantity of flow and of storage are most profitable.

Application to the water-balance determination

The determination of the water-balance by stream-flow technique has certain profitable aspects as well as some disadvantages. In the sequence, rainfall—capillary penetration—sub-surface run-off, the stream bypasses the plant. In this sequence interception in the canopy represents the storage in the section of the plant, but, in this section, the stream-flow is of no importance. In the sequence, sub-soil irrigation—upward capillary flow—flow through stems and leaves—vertical vapour transport in the atmosphere, the flow resistance in the plant has to be taken into account, but in this sequence, storage in the plant is negligible.

In the atmosphere storage is of no interest. With rainfall there is no flow resistance and with evaporation this resistance can accurately be included in one of the formulae for potential evaporation. For small crops, very often, interception is not determined. This is a limited disadvantage, because the intercepted water will seldomly stay on the leaves for a long time and over a longer period it may readily be included with the rain that reaches the soil or with the water that evaporates.

The water-balance determination may be simplified to a marked extent. If the sections corresponding to plant and atmosphere can be omitted, only three potentials are required. For the sequence of the upward flow one may restrict oneself to the determination of the water level in the ditch, of the groundwater level and of the potential evaporation. The rainfall is the fourth observation that is required for the downward flow and for the absolute basis from which the series of stream-flow relations can be calculated in terms of actual flowing quantities.

The formula for stream-flow and storage

For the formula for flow a choice can be made between steady and non-steady conditions. Several formulae of each kind are given in literature. Both types of formulae have limitations. Because the steady flow formula is simplest, it is the most attractive. Where necessary the formula for tile drainage spacing is used.

Groundwater storage is so linked up with steady capillary storage, that these two are best treated together.

Capillary flow can, up to now, be described only in a formula for the steady case. Because even this formula is somewhat complicated, a nomograph was constructed to check the results of the graphical analyses.

Storage may be read from the same nomograph, which gives the relation between moisture content, groundwater depth and quantity of capillary stream-flow. The differences in moisture content in the profile for different depths of the water table and different amounts of capillary flow give a more practical insight in these investigations than the absolute values of moisture content. For a variation of 1 mm. of flow a day or a water level rise of 10 cm., this difference in storage may be calculated from the nomograph and used for comparison with the graphical solution, provided pF-curves for the different layers of the profile are available.

Besides the steady capillary storage, an unsteady storage has to be distinguished. This unsteady capillary storage corresponds to the water stored directly after a rain-shower during the period this amount of water is not yet distributed as capillary moisture according a steady state moisture profile. After some time, it will be distributed through the profile in conformity with the moisture content given by steady capillary flow. As far as present experience goes, in a normal agricultural soil this unsteady situation lasts only a part of a day. The rainfall of the preceding day is the most useful parameter. The accuracy of the solution of the water-balance for time intervals of 14 days is not materially decreased if this term is disregarded.

The formula for capillary flow only covers the flow through the soil. The flow through the plant has also to be described by a formula based on some physical conception if one wishes to check the empirical quantity of

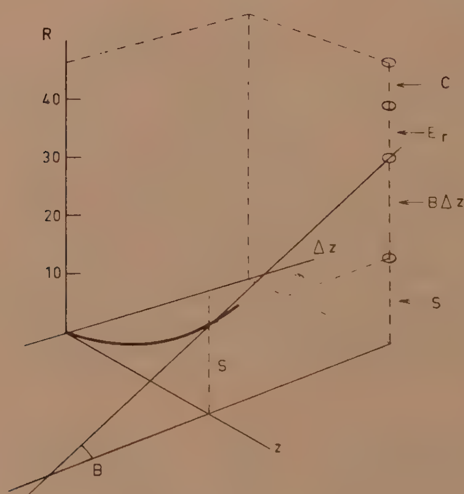

Fig. 1 The possibility of solving, in principle, the equation of the water-balance follows from the solid diagram. Rainfall R is split up into the discharge S, storage $B \Delta z$, actual evaporation Er and unsteady storage C. The parameters for these various quantities differ and are for S: z, for B: Δ z, for Er: Eo, R and z, for C: time t. Because the parameters are not mutually dependent the equation can be solved

flow by a fundamental formula. Here lies the main difficulty. There does not yet exist any formula which gives the relation between potential and actual evaporation as a function of the moisture tension in the root zone. This problem has still to be tackled entirely empirically.

The graphical method

The graphical solution is based on the identity of run-off, storage and evaporation on the one hand and rainfall on the other (fig. 1). In 3-dimensions one may, for 14 day periods, plot rainfall R, groundwater depth minus depth of the water in the ditch z and the rise of the watertable within the 14 days $\triangle z$. In this figure a curved surface has to be constructed which, at the intersection with planes parallel to the R-z plane, corresponds to the steady runoff S. Steady flow is defined by $\triangle z$ = zero. At points of intersection with planes parallel to the R-$\triangle z$ plane, the storage B is depicted. Now the difference introduced by the rainfall R is equal to the sum of the real evaporation Er and the unsteady capillary storage C. Evaporation is mainly a function of the capillary potential in the root-zone. If this potential is not known, it may be replaced by the rainfall during the fortnight. Rainfall as an evaporation parameter, however, makes the solution of the water-balance much more difficult because several very disturbing correlations are introduced in this way. The non-steady storage is strongly related to the rainfall on the day preceding the reading of the water-table depth. Because of the slight influence of this non-steady storage, this term of the balance is best omitted if no figure for capillary potential is available.

Now the space, in which the points for each observation may be assumed to be dispersed, is divided into small intervalls parallel to the R-$\triangle z$ plane as well as to the R-z plane in such a way, that within each interval, sufficient readings are present. For each interval lines of average are drawn through the points as freehand curves and a check is made that the lines in both directions do not cross over each other, but intersect. In this case they are part of the same plane. If the formulae were sufficiently well established, the curves might be fitted by least squares. The plane is determined for groups of observations with more or less the same value for the potential evaporation.

If run-off curves are constructed for different values of potential evaporation this must give a discharge curve of identical shape for each level of evaporation. In the space diagram, where as a first approximation rainfall is taken as a measure for sub-surface run-off, the curves will show a vertical displacement for different values of potential evaporation. This vertical displacement accounts for the differences in real evaporation, which should be substracted from the amount of rainfall to find the real run-off. The displacement compared with the curve for the winter months with low evaporation gives the first approximation for the real evaporation. The curve gives the first approximation for the sub-surface run-off.

Run-off

In figure 2, the first approximation for the run-off is given. By a reiterative procedure, in which the estimates for run-off, storage and evaporation are gradually improved, the accuracy may be increased. The last results are checked by comparing them with the drainage formula

$$\frac{S}{z} = A + Bz \qquad \text{where,} \quad A = \frac{8\,kd}{l^2}$$

$$B = \frac{4\,k}{l^2}$$

S = run-off
z = pressure-head
A, B = constants for the same place in the terrain
k = permeability
d = thickness of aquifer
l = distance between drains or ditches

The test of the straight line relation by plotting $\frac{S}{z}$ against z as given by this formula is valuable though it is not very precise, because of inherent errors in the data and the limited variations in run-off. A better test is a comparison with run-off determined in the same area with lysimeters. This has been done for data from the Rottegatspolder. Figure 3 gives this result showing an error of 9 mm. for the run-off over 14 days.

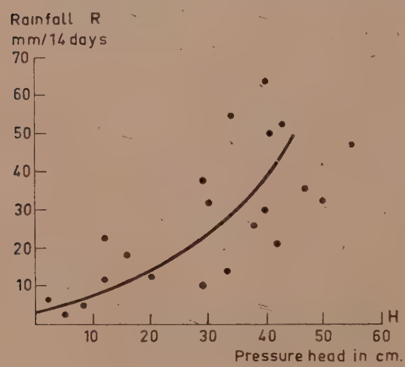

Fig. 2 Relation between rainfall intensity and the pressure head in a testwell with respect to the ditch-water level. The curve is valid for rainfall and evaporation over 14 days. The data were selected for intervals of 0—8 mm. of evaporation from open water and a fall of the water table during these 14 days of 20 cm

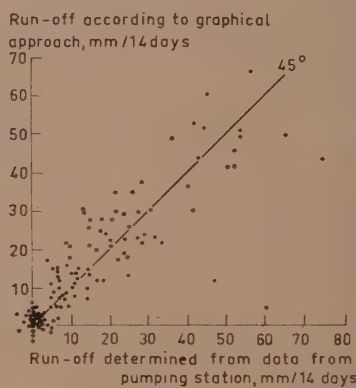

Fig. 3 Comparison between the discharge of the catchment area taken form the discharge data of the pumping station and the discharge determined by the graphical analysis

STORAGE

The value for the storage capacity—the increase in moisture retention for a groundwater variation of 10 cm.—is a function of the groundwater depth and the excess of rainfall over real evaporation, whether positive or negative. For a restricted number of intervals of rainfall-excess and groundwater depths the storage data-obtained by subtracting run-off and evaporation from rainfall—are plotted against groundwater depth or rainfall-excess.

The curves for storage—to which the storage capacity is the tangent—are given in figure 4 for the fortnigths with an evaporation from the free water surface of 4 mm. in 14 days with increasing groundwater depths. If from these graphs the tangents are determined and plotted against groundwater depth and rainfall-excess a result such as given in figure 5 is obtained.

To test this result, the storage for this profile, for the same stream-flow intensity and various groundwater depths, was taken from the nomograph for capillary flow and the pF-curves for this profile. This comparison is given in figure 6. The curves found by the graphical analysis are sufficiently of the same type, but are obviously displaced to the right. It may be presumed that this is due to the cracks in this heavy acid clay, which do not appear in the soil samples taken for the pF-determinations because these samples are too small. The cracks may be several cm. wide and several dm. apart. Comparison of the two sets of curves leads to the assumption that the volume of these cracks will be 5% smaller in winter than in summer. This seems not unreasonable; there is no direct test for this, however. Because the determination of the volume of cracks does not appear to have an easy practical solution this might remain with heavy clays one of the difficulties for the future.

The calculated storage was tested by comparing it with the data for the moisture contents determined in the lysimeter area of the Rottegatspolder. Figure 7 gives this result; the error in this case is 14 mm.

Evaporation

If the corrected values for run-off and storage are subtracted from the rainfall, these data may be sorted out according to particular intervals of potential evaporation, rainfall and groundwater depth. There exists a

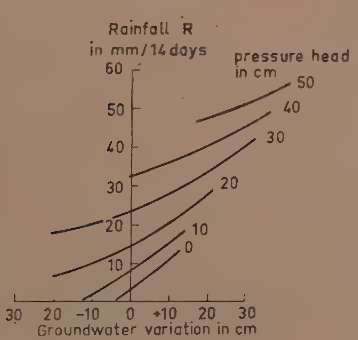

Fig. 4 Relation between change in groundwater level, rainfall and pressure head for periods with an average of 4 mm. evaporation from an open water surface for a time interval of 14 days. The inclination of the lines is a measure for the storage capacity

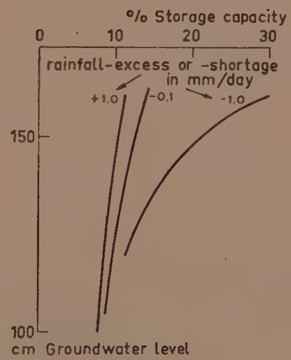

Fig. 5 The storage capacity varies according to the depth of the groundwater table and the direction and intensity of the capillary flow. The results of the analysis are given for zero flow, downward flow (+ 1.0) and upward flow (— 1.0)

strong correlation between potential evaporation and groundwater depth, which may only be overcome by collecting together the data from a few observation points within the same profile but with different water depths. This was not possible in this flat lysimeter area, so that no separation of the influence of water depth and potential evaporation could be made. Undulating land has, in this respect, an advantage over flat land.

The real evaporation plotted against potential evaporation for different depths of groundwater is depicted in figure 8. Because no theory on the exact shape and position of these lines exists and the accuracy and the distance between extremes does not permit any finer details, straight lines were drawn through the scatter-diagrams. It is obvious that the curves must leave the origin at an inclination of about 45° and reach a maximum somewhere, corresponding with the highest possible evaporation, this maximum-curve being due to increased flow resistance in the plant and the soil.

In figure 9, the same data are arranged according to rainfall, with various values for evaporation from a free water surface. Here the same applies, that the curves at some level of actual evaporation will approach a horizontal asymptote. They, however, do no start from the origin but from a point which indicates the capillary supply of water, in agreement with the depth of the groundwater level and the moisture tension in the root-zone.

What is not yet clear in this result is the influence of the depth of the water table on the evaporation, because the capillary potential in the root-

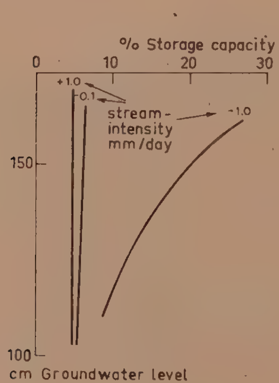

Fig. 6 From data of the moisture characteristic curve and the formula for steady capillary flow the air content of the soil may be calculated for the same capillary streamflow intensities as given in fig. 5. The difference in the position of the curves gives an indication of the influence of the non-capillary pore space of the coarse soil structure which is not taken into account in determining the moisture characteristic curve

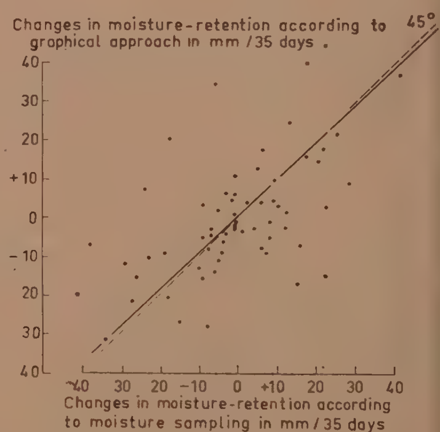

Fig. 7 In the Rottegatspolder lysimeter experiment the changes in moisture content of the profile are determined by soil sampling. These moisture content variations may also be calculated from the graphical analysis in fig. 5. The scatter diagram shows the extent to which the two sets of data agree

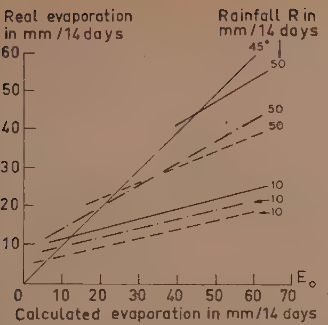

Fig. 8 Actual evaporation is governed by the evaporating capacity of the atmosphere given by the Eo value and the rainfall during the period. The depth of the water table — at the same time a measure for moisture depletion of the soil — also exerts an influence

water-table 155 cm. — full line
water-table 135 cm. — dashed line
water-table 115 cm. — dash-dot

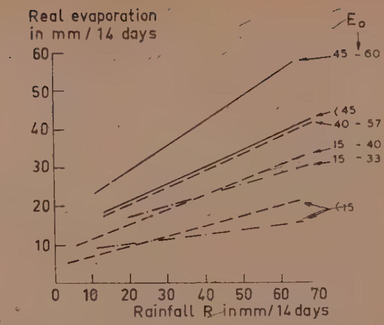

Fig. 9 The four dimensional relation between actual evaporation, rainfall, evaporating capacity and groundwater depth, shown in fig. 8, may be presented in another projection, showing how heavily rainfall influences actual evaporation. The lines represent the mean of the interval of Eo, given in the graph, and the depth of the water table indicated by the different lines, as mentioned in fig. 8

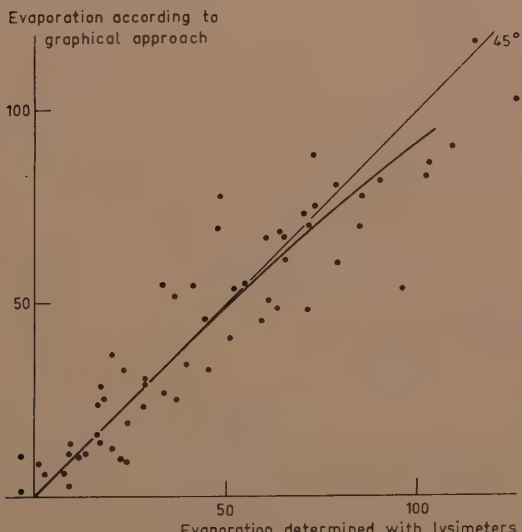

Fig. 10 The Rottegatspolder experiment yielded results for the evaporation from the lysimeter plots for time intervals of 35 days. From the graphical analysis the evaporation over the same intervals was calculated and plotted against the lysimeter results. The result is given in this scatter digram. The mean error proved to be 12.5 mm. of moisture

zone is not known and an indirect solution cannot be given with a sufficient accuracy. The intercepts of the lines in figure 9 with the vertical axis cannot be tested. It is clear that some relation between the intercepts—the evaporation in absence of rain—and the depth of the groundwater must exist. It is not known if influences of the plant also have to be taken into account.

The accuracy of the results was again checked with the results of the lysimeters of the Rottegatspolder. Figure 10 gives the result of this test. Here the mean error is 12.5 mm. for the evaporation over 35 days. This is about the same error as was found in the test of run-off and storage. If the error of the direct determination is put at approximately 5 mm., it is clear that the error of the result of the stream-flow approach will remain above 10 mm. Some increase in accuracy may be achieved if a numerical adjustment, based on a good physical formula, becomes available. Adjustment with casual empirical functions will not improve much upon the results now obtained and will probably give worse results. It is obvious that the moisture flow technique cannot claim to give the same accuracy as direct determinations. On the other hand it is less costly and less time consuming.

Some final remarks

The stream-flow approach necessitates an explicit expression of what the process is expected to be, that distributes rainwater as storage, evaporation and run-off. Where water table depths are observed over a number of years, frequently and regularly, these data may supplement, to a greater of lesser extent, drainage trials, run-off measurements, groundwater depth trials and lysimeters. The work in the field is limited, the costs of the experiment are negligible, but the amount of work to be done at the desk is still very extensive.

Where the depth of the water table is very great, where the variations in water depth or evaporation are small, where the depth of the permeable layer is very variable or where, at peak run-off, the water flows over the land, or, at lower run-off values, through fissures in rocks, there the measurement of the groundwater depth, discussed here, may not be applicable. In these cases, the prospects of a simple application of the stream-flow technique with water depth determinations do not seem too bright. It is however possible to neglect under these circumstances, the problems of the saturated zone. With tensiometers at different depths it appears possible to determine how much water sinks below a depth at which no plant has any influence. This water will eventually help to stock the groundwater and add to the sub-surface run-off.

Quick and simple determinations regarding the width of the opening of the stomata in the leaves—already in use for advice on sprinkling irrigation—might provide a very promising supplement to the other determinations. They may promote a better understanding of water use by the plant or at least increase our knowledge where it is weakest. Also, potential determinations on lysimeters or self-recording moisture determinations with the new γ-ray apparatus in the field without a lysimeter, may add to our knowledge and enable us to develop the functional formulae of the water-balance, which will strongly promote the study of water relations in the field. The lysimeter will remain the cornerstone of water-balance studies; it should not, however, be looked upon as the only and entire foundation of this branch of science.

ACKNOWLEDGEMENT

In this article we have taken a great amount of data from the Rottegatspolder experiment. This experiment was set up by the Ministry of Rijkswaterstaat and it is executed under the supervision of the Working Group on Evaporation Research of that Ministry. The experiment is carried out with a number of lysimeters, situated in a small catchment area and discharge data of the pumping station of that area are collected. The results of the evaporation determination for the catchment area are tested with those of the lysimeter. These data were particularly suitable for the testing of the field method of water-balance investigation, described above.

Our thanks are due to Dr. L. J. L. Deij, Director of the Division for Climatology and Agricultural Meteorology of the Royal Netherlands Meteorological Institute, Chairman of the Working Group on Evaporation Research, for his consent to use the results of the investigations of the Rottegatspolder. We are also grateful to Ir. A. Volker, Head of the Water Management Department of the Ministry of Rijkswaterstaat, for making the data available. Extremely valuable to our investigations were the data on the moisture content of the soil, collected under the supervision of Dr. P. K. Peerlkamp, Head of the Agricultural Department of the Institute for Soil Fertility.

The data, used for this study, were taken from the Annual Reports of the Working Group over the years 1951—1956.

We have appreciated very much the kindness of Dr. L. Leyton of the Department of Forestry, Oxford, to read the manuscript. We have made large use of his valuable suggestions.

VERSUCHE ZUM PROBLEM DES OBERFLÄCHENABFLUSSES BEI WALD- UND WEIDEBÖDEN

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SUMMARY

The Swiss Forest Research Institute, in the catchment areas of its water measuring stations, attaches great importance to the elucidation of all questions connected with the surface run-off of the precipitation on the pasture and in the forest. On the basis of previous experiments an endeavour is made to show the different aspects possible. The problem is particularly actual in the region of the water measurement stations established, in 1951/52, in the Flysch region of Schwarzsee in the Canton Freiburg. The soils of that region, rich in clay, are poorly permeable and easily wetted, and therefore facilitate the surface run-off, especially during heavy rainfall. This phenomenon, which causes flood peaks and inundations, is much more intensive in pure pasturages than in forest areas, as could be proved by artificial rainfall and infiltration tests. In spite of the fact that the results communicated are of provisory character, they may be welcome as a basis for discussion.

RÉSUMÉ

L'Institut suisse dè recherches forestières attache beaucoup d'importance à ce que, dans les bassins de réception de ses stations hydrométriques, toutes les questions relatives à l'écoulement superficiel des précipitations en pâturage et en forêt soient élucidées. Sur la base d'essais déjà effectués, le rapport s'efforce de présenter les divers aspects possibles. Le proplème est particulièrement actuel dans le perimètre des stations hydrométriques crées en 1951/52 dans la région de Flysch du Lac noir, au canton de Fribourg. Les sols très riches en argile y sont généralement peu perméables, deviennent facilement mouilleux et favorisent en conséquence l'écoulement superficiel, en particulier lors des pluies d'orages. Ce phénomène, qui provoque des crues et des inondations, se produit d'une manière beaucoup plus intense dans les pâturages purs que dans les parties boisées, ainsi que cela a pu être démontré à l'aide d'essais d'arrosage et d'infiltration. Bien que les résultats communiques aient un caractère provisoire, ils pourront peut-être servir comme base de discussion.

Die bisherigen Untersuchungen über den Wasserhaushalt von Einzugsgebieten der Bäche und Flüsse haben ergeben, daß die Abflußverhältnisse, je nach der Art der Vegetationsdecke, sehr verschieden ausfallen können. Insbesondere trifft dies zu, wenn es sich einerseits um Waldgebiete, andererseits um Weidegebiete handelt. Immer wieder hat sich, unter sonst gleichartigen Verhältnissen, gezeigt, daß im ersteren Falle die Hochwasserspitzen viel gemäßigter sind, und als Hauptgrund hierfür wird die größere Wasseraufnahmefähigkeit und die größere Wasserdurchlässigkeit des Waldbodens, gegenüber dem Weideboden, angeführt. Dabei darf allerdings nicht übersehen werden, daß auch der Waldboden nicht beliebig viel Wasser zu speichern vermag, und daß sich daher bei lang andauernden Regenperioden die Unterschiede zwischen den beiden Kulturarten weitgehend verwischen können. Am eindrücklichsten zeigt sich dagegen das verschiedenartige Verhalten bei intensiven Gewitterregen nach einer vorangegangenen Trockenperiode. Sicker-

versuche haben ergeben, daß guter Waldboden eine bestimmte Wassermenge um ein Vielfaches rascher aufzunehmen vermag als ein typischer Weideboden. Die Menge des oberflächlich abfließenden Niederschlagswassers, welches für das Ausmaß der Hochwasserspitzen bestimmend ist, muß daher auf der Weide ungleich größer sein als im Walde. Um diese aus dem Verlauf von Abflußkurven abgeleitete Behauptung zu beweisen, wurden in verschiedenen Ländern Oberflächenabflußversuche durchgeführt. Seitens der Schweizerischen forstlichen Versuchsanstalt wurden solche Messungen im Einzugsgebiet unserer Wassermeßstationen im Emmental, im Tessin, im Schwarzseegebiet im Kanton Freiburg, sowie im Bereich der Baye de Montreux am Genfersee, vorgenommen. Aber auch im überseeischen Ausland hat man das Problem seit langem aufgegriffen. Es sei hier nur an die Messungen von Coster auf Java und die überaus zahlreichen Untersuchungen in den Vereinigten Staaten von Nordamerika erinnert. Auch in Westdeutschland ist neuerdings das Interesse an derartigen Untersuchungen groß, wie dies besonders die Oberflächenabflußmessungen von Hesmer und Feldmann im südlichen Sauerland, sowie diejenigen von Delfs und Kiesekamp im Oberharz dartun.

Generell muß man unterscheiden zwischen Anlagen, die sich mit dem Oberflächenabfluß des natürlichen Niederschlages befassen und solchen, die mit künstlicher Beregnung arbeiten. Im ersteren Falle handelt es sich um stationäre Installationen, die langfristig betrieben werden, und die neben dem Vorteil der Erfassung des tatsächlichen Oberflächenabflusses auch noch gestatten, die Erosionsbeträge zu messen. Bei den Versuchen mit künstlicher Beregnung hat man dagegen die Möglichkeit, die Niederschläge zeitlich und mengenmäßig nach Wunsch zu dosieren. Es handelt sich dabei meist um kurzfristige Untersuchungen, die aber stichprobenartig über eine größere Fläche verteilt werden können. Im Folgenden soll nur von dieser Art der Messungen die Rede sein. Alle hier aufgeführten Untersuchungen wurden im Zusammenhang mit den Forschungen von Professor H. Burger durch dessen Mitarbeiter E. Casparis vorgenommen.

In Tabelle 1 sind einige Beispiele von Oberflächenabflußmessungen zusammengestellt. Überblickt man diese, so fallen in erster Linie die hohen Abflußprozente der reinen Weideflächen und die durchwegs viel geringeren bis fehlenden Abflüsse im Walde auf. Ein strenger Vergleich ist jedoch nur innerhalb der gleichzeitig untersuchten Objekte erlaubt, da Unterschiede im momentanen Wassergehalt der Böden die Resultate wesentlich verändern können. In Tabelle 1 ist z. B. bei den Oberflächenabflüssen der Baye de Montreux ein merklicher Unterschied zwischen den Resultaten von 1936 und 1937 festzustellen, der zweifellos auf verschiedene Wassergehalte des Bodens zurückzuführen ist. Die beobachteten höheren Abflüsse von 1936 wurden unmittelbar nach dem Schmelzen eines frühen Schneefalles registriert, während die niedrigeren Werte von 1937 drei Tage nach dem letzten Niederschlag gemessen wurden. Große Oberflächenabflüsse sind z. B. bei stark ausgetrockneter Bodenoberfläche zu erwarten; dies jedoch nur bis zur Überwindung des Benetzungswiderstandes. Eine zweite kritische Phase tritt in der Regel erst wieder ein, wenn sich der Wassergehalt des Bodens dem Sättigungspunkt nähert, während bei mittleren Graden der Bodendurchfeuchtung offenbar keine deutliche Abhängigkeit zwischen Oberflächenabfluß und Wassergehalt des Bodens besteht.

Man wäre auch leicht geneigt, anzunehmen, daß der Neigungswinkel der beregneten Flächen einen großen Einfluß auf den Oberflächenabfluß ausübe. Schon die Untersuchungen von Duley und Hays haben aber gezeigt, daß

zwar bei einer Zunahme der Hangneigung von 0 % auf 3 % auch der Abfluß rasch zunimmt, darüber hinaus dagegen nur noch in sehr geringem Ausmaße. Zum gleichen Ergebnis gelangten in neuerer Zeit Hesmer und Feldmann, die für Hangneigungen von 11 bis 40 % keine eindeutigen Zusammenhänge zwischen Gefälle und Oberflächenabfluß feststellen konnten. Auch in Tabelle 1 fällt auf, daß letzterer gerade bei den größten Hangneigungen sehr klein ist. Im Emmental z. B. wollte es der Zufall, daß auf der Weide der Versuch mit dem kleinsten Abfluß von nur 13 % bei der größten Hangneigung von 75 % eintrat, während dem größten Abfluß von 78 % eine Hangneigung von nur 36 % entsprach. Das Ausmaß der Erosion dagegen ist nach den Untersuchungen von Coster sehr stark durch die Geländesteilheit bedingt.

Von wesentlich größerem Einfluß als die Hangneigung sind offenbar andere Faktoren, wie z. B. die Beschaffenheit der Bodenoberfläche, des Bodengefüges oder der alles überragende Einfluß der Vegetation. Gegenüber der reinen Weide macht sich schon eine leichte Verwilderung durch Gebüsche, Farne, Beersträucher oder Calluna in einer Verminderung des Oberflächenabflusses bemerkbar. Wie das Beispiel der Baye de Montreux zeigt, dürfte

TABELLE 1

Oberflächenabfluß in Prozenten der künstlichen Beregnung von 100 mm in 100 Minuten (Mittelwerte)

Ort der Untersuchung	Jahr	Vegetationsart	Hangneigung %	Oberflächenabfluß in % d. Niederschl.
Emmental (Kt. Bern)	1940	Saubere Großviehweide	48	51
		Mit Alpenerlen durchsetzte Weide	72	3
		Mit Adlerfarn durchsetzte Weide	60	5
		Plenterwald	69	0
Melera (Kt. Tessin)	1943	Saubere Großviehweide	52	62
		Mit Adlerfarn durchsetzte Weide	77	15
		Buchenniederwald und Nadelholzaufforstung	71	10
Baye de Montreux (Kt. Waadt)	1936	Alpweide in Betrieb	46	78
		Alpweide nach 7 Jahren Weideausschluß	45	12
dito	1937	Alpweide in Betrieb	50	60
		Alpweide nach 7 Jahren Weideausschluß	52	0
Schwarzsee (Kt. Freiburg)	1948	Saubere Großviehweide	45	77
		Beweideter, wenig zertretener Fichtenwald	30	31

aber bereits auch der Ausschluß der Beweidung, und damit die Verhütung einer dauernden Bodenverwundung und Bodenverhärtung, ausreichen, um den Oberflächenabfluß in kurzer Zeit merklich zu senken.

Einige wenige Versuche geben schon ein recht deutliches Bild über die prinzipiellen Unterschiede zwischen den beiden Vegetationsarten. Falls man aber für ein bestimmtes, größeres Gebiet auch quantitativ einwandfreie Angaben benötigt, müssen sehr viele Oberflächenabflußmessungen durchgeführt werden, um eine Verfälschung durch die zahllosen in der Natur auftretenden Imponderabilien auszuschalten. Darüber hinaus ist aber auch die Art der Messung, die natürlich viele Variationen zuläßt, von großem Einfluß auf die Resultate. Gewöhnlich geht man dabei so vor, daß im Gelände ein bis wenige Quadratmeter einheitlicher Fläche für die künstliche Beregnung ausgesucht werden. Am unteren Ende der Probefläche wird sodann ein kleiner Graben ausgehoben und eine Blechrinne so an der oberen Grabenwand angebracht, daß der oberflächlich abfließende Niederschlag darin aufgefangen und in ein geeignetes Meßgefäß abgeleitet werden kann. Um ein seitliches Entweichen des Niederschlags zu verhüten, wird gewöhnlich auf beiden Seiten ein Blechrahmen in den Boden gedrückt. Vielfach ist dies aber nicht möglich und es empfiehlt sich daher, die Blechrinne etwas über die beregnete Fläche vorspringen zu lassen. Da es beinahe unmöglich ist, den Rand der Rinne genau an der Bodenoberfläche anzubringen, ist man meistens gezwungen, diese Ansatzstelle etwas tiefer zu legen. Bei unseren eigenen Versuchen lag sie im Mittel etwa 5 cm unter der eigentlichen Bodenoberfläche, bei den Versuchen von Hesmer und Feldmann etwa 2—3 cm. Der Begriff Oberflächenabfluß wird dadurch natürlich etwa verwischt und der Vergleich mit anderweitigen Untersuchungen erschwert.

Je größer die Probefläche gewählt wird, um so mehr werden natürlich Zufälligkeiten in der Bodenbeschaffenheit und der Vegetationsdecke ausgeschaltet. Sehr oft muß man aber das benötigte Beregnungswasser von ziemlich weither mühsam herbeischaffen und aus diesem Grunde mit kleineren Flächen vorlieb nehmen. Bei den in Tabelle 1 enthaltenen Beregnungsversuchen beschränkte man sich auf Flächen von 1 Quadratmeter Größe, während bei den besonders zahlreichen Versuchen von Hesmer und Feldmann im Sauerland die doppelte Flächengröße zur Anwendung kam, wobei die Breite parallel zum Hang 1 m, die Länge in der Hangrichtung 2 m betrug. Der Einfluß der Flächengröße auf den Oberflächenabfluß wurde von Coster eingehend untersucht. Bei Beregnungsflächen von 1 m Breite und 3 m Länge erhielt er keineswegs den 3fachen Abflußbetrag von nur 1 m² Fläche, sondern bloß den $1^1/_2$- bis 2fachen Betrag. Größere Anlagen von 4 × 16 m zeigten bei der Verkürzung auf die Hälfte ebenfalls einen relativ zur Fläche größeren Abfluß. Diese Erscheinung dürfte ganz allgemein zutreffen, so daß man bei kleinen Versuchsflächen ein gegenüber dem ganzen Hang zu großes Abflußprozent erhält. Im Falle der Coster'schen Untersuchungen wird diese Tatsache dadurch noch verstärkt, daß die Beregnung bis unmittelbar an den Grabenrand erfolgte. Ein beträchtlicher Teil des Niederschlages gelangt hier aber gar nicht erst auf den Boden, sondern fließt über Streuauflagen, längs abgestorbenem Gras etc. direkt in die Rinne und täuscht so einen merklich höheren Oberflächenabfluß vor, der natürlich um so stärker ins Gewicht fällt, je kleiner die beregnete Fläche ist. Hesmer und Feldmann bezeichnen diese in Amerika als tile-effect bekannte Erscheinung als Diagonalversickerung. Zu deren Verhütung ist es angezeigt, zwischen den beregneten Flächen und dem Grabenrand einen unberegneten Streifen von 10 bis 20 cm Breite einzuschalten, wie dies auch bei den hier behandelten Beispielen geschah.

Um überhaupt sicher meßbare Oberflächenabflüsse zu erzielen, muß gewöhnlich in einem Ausmaß beregnet werden, welches die Intensität von natürlichen Niederschlägen weit übertrifft. Bei den Versuchen im Sauerland betrugen die maximalen Dosierungen 50 mm, bei einer Niederschlagsintensität bis zu 4 mm pro Minute. Bei den in Tabelle 1 aufgeführten Beispielen wurde eine einheitliche Beregnung von 100 mm Niederschlag angewandt, mit Ausnahme der Versuche in der Baye de Montreux, wo nur mit 50 mm beregnet wurde. Das Vorgehen dabei war folgendes: Zunächst wurden 10 mm Niederschlag innert 5 Minuten, zeitlich und mengenmäßig möglichst gleichmäßig, auf die Probefläche verteilt. Nach einer Wartefrist von weiteren 5 Minuten, während welchen die nötigen Messungen und Beobachtungen vorgenommen wurden, erfolgte in genau gleicher Weise eine zweite Beregnung und so fort, bis zur Erreichung von 100 mm Niederschlag in 100 Minuten. Die Niederschlagsintensität für die ganze Beregnungsdauer betrug also einheitlich 1 mm pro Minute, und innerhalb des Versuches, d. h. unter Ausschaltung der Wartefristen, 2 mm pro Minute. Es handelt sich also um Intensitäten, die in der Natur kurzfristig häufig vorkommen können. Über eine ganze Stunde andauernd sind solche Starkregen jedoch äußerst selten. Sie liegen aber immerhin noch im Bereich des Möglichen. So sollen z. B. laut Zeitungsberichten bei der Unwetterkatastrophe in Oberbayern und Österreich von Mitte Juni 1959 bei Kufstein innerhalb einer Stunde 66 mm Niederschlag gefallen sein, d. h. 1,1 mm pro Minute.

Es wäre sehr zu begrüßen, wenn anläßlich des Symposiums in Hann.-Münden in engerem Interessentenkreise über alle diese Fragen diskutiert werden könnte, um für die Untersuchungen der verschiedenen Forschungszentren eine einheitlichere Methode festzulegen, die den Vergleich der Resultate erleichtern würde. Dabei ist mir vollständig bewußt, daß, sowohl die natürlichen Gegebenheiten an verschiedenen Orten, sowie die Art der Fragestellung vielfach Abweichungen von einer solchen Norm notwendig machen werden, und ich möchte diese auch nur als allgemeine Richtlinie aufgefaßt wissen.

Die Schweizerische Anstalt für das forstliche Versuchswesen ist im Gebiet ihrer 1951/52 geschaffenen Wassermeßstationen beim Schwarzsee im Kanton Freiburg ganz besonders am Problem des Oberflächenabflusses interessiert. Die beiden dortigen Einzugsgebiete liegen in der Flyschzone, deren sandigtoniger Boden schwer durchlässig ist, leicht vernäßt und daher einen starken oberirdischen Abfluß begünstigt. Im Jahre 1948 wurden in dieser Gegend als Vorstudien einige Bodenuntersuchungen und Oberflächenabflußmessungen vorgenommen, auf die ich noch kurz eintreten möchte. Dabei sei aber ausdrücklich darauf hingewiesen, daß diese wenigen Versuche lediglich zur Erläuterung der Untersuchungsmethode und als allgemeine Richtlinie zu betrachten sind, daß aber zur Gewinnung sicherer Mittelwerte noch weitere Messungen notwendig sind.

Wie aus Tabelle 2 hervorgeht ist die Wasserkapazität bei den Schwarzseeböden merklich höher als in den Einzugsgebieten des Emmentals. Sie liegt in der gleichen Größenordnung wie bei den Böden der Wassermeßstation Melera im Tessin. Trotzdem bestehen bezüglich der Durchlässigkeit zwischen diesen beiden letzteren Bodentypen ausgesprochene Unterschiede, die sich nur durch eine verschiedenartige Porengrößenzusammensetzung und eine unterschiedliche Luftkapazität erklären lassen. Daß letztere in den lockeren Moränenböden von Melera bedeutend höhere Werte aufweist als in den dicht gelagerten Flyschböden beim Schwarzsee, geht aus Tabelle 2 deutlich hervor. Leider wurden bis jetzt keine Korngrößenanalysen aus-

TABELLE 2

Wasserkapazität, Luftkapazität und Gesamt-Porenraum in Volumenprozenten des natürlich gelagerten Bodens in 0—10 cm, 20—30 cm und 50—60 cm Tiefe

Ort der Untersuchung	Vegetationsart	Wasserkapazität			Luftkapazität			Porenraum		
		0—10 cm	20—30 cm	50—60 cm	0—10 cm	20—30 cm	50—60 cm	0—10 cm	20—30 cm	50—60 cm
Emmental 1936	Weide	54.0	45.4	43.2	4.0	4.9	4.9	58.0	50.3	48.1
	Wald	51.6	44.4	39.2	11.6	7.0	7.1	63.2	51.4	46.3
Melera 1936	Weide	68.6	61.3	—	6.7	6.9	—	75.3	68.2	—
	Wald	65.3	64.0	—	14.8	8.3	—	80.1	72.3	—
Schwarzsee 1948	Weide	68.4	58.3	57.0	3.5	3.4	2.6	71.9	61.7	59.6
	Wald	66.4	50.5	48.4	10.2	4.7	2.8	76.6	55.2	51.2

geführt, so daß die diesbezüglichen Unterschiede, die okular sehr gut zu erkennen sind, nicht zahlenmäßig untermauert werden können. Bei früheren Untersuchungen im Höllbachgebiet, welches die gleichen Bodenverhältnisse aufweist wie das Schwarzseegebiet, lag der Steingehalt des Bodens, d. h. der Anteil der Körner über 2 mm Durchmesser, unter einem Gewichtsprozent des trockenen Bodens, während die Körner unter 0,02 mm Durchmesser $^1/_3$ bis nahezu $^1/_2$ des Feinerdegewichtes ausmachten.

Vergleicht man bei den Schwarzseeböden die Verhältnisse in verschiedenen Bodentiefen, so zeigt sich für die oberste Bodenschicht von 0—10 cm Tiefe im Walde eine etwas geringere Wasserkapazität als auf der Weide. Da aber die Luftkapazität in dieser Tiefe im Walde ungefähr dreimal größer ist als auf der Weide, ergibt sich für den Wald trotzdem ein deutlich größerer Porenraum. In den tieferen Bodenschichten nimmt aber bei beiden Vegetatiosformen sowohl die Wasser- wie auch die Luftkapazität rasch ab, und zwar im Walde relativ rascher als auf der Weide, so daß in 50—60 cm Tiefe die Wasserkapazität des Waldes merklich unter derjenigen der Weide liegt, während die Luftkapazität in beiden Fällen ungefähr auf den gleichen Wert absinkt. Die günstige Wirkung des Waldbodens auf das Wasserregime wird also weitgehend durch die oberste Bodenschicht bedingt. Ohne Korngrößenanalyse ist es aber auch hier schwierig, die Bedeutung dieser verschiedenartigen Verminderung des Porenraumes auf die Wasserspeicherung und Wasserdurchlässigkeit richtig einzuschätzen.

Ein gutes Mittel zur Veranschaulichung der unterschiedlichen Wasseraufnahmefähigkeit von Wald- und Weideböden ist der Sickerversuch, bei dem die Zeit festgestellt wird, deren es zur vollständigen Versickerung einer Wassersäule von 100 mm Höhe durch ein 10 cm tief in den Boden versenktes Rohr von 1 dm^2 Querschnittsfläche bedarf. Tabelle 3 zeigt, wiederum für die Wald- und Weideböden unserer drei Wassermeßstationen, die vor und nach der künstlichen Beregnung erzielten Sickerzeiten. Auch hier ist ein direkter Vergleich nur zwischen Wald und Weide der einzelnen Örtlichkeiten zulässig. Überall zeigt der Waldboden eine wesentlich kürzere Einsickerungsdauer als der Weideboden. Im Emmental ergibt sich vor der Beregnung ein diesbezügliches Verhältnis von 1 : 48, nach der Beregnung von 1 : 34. In Melera ergeben sich hierfür 1 : 7, resp. 1 : 4 und im Schwarzseegebiet 1 : 4,

TABELLE 3

Einsickerungsdauer für 100 mm Wassersäule vor und nach der Beregnung mit 100 mm Niederschlag

Ort der Untersuchung	Vegetationsart	Vor der Beregnung				Nach der Beregnung			
		h	'	"	Verhältnis Wald : Weide	h	'	"	Verhältnis Wald : Weide
Emmental	Weide	1	43	39	1 : 48	3	36	28	1 : 34
1940	Wald	—	2	10		—	6	24	
Melera	Weide	—	35	22	1 : 7	—	53	56	1 : 4
1943	Wald	—	5	12		—	12	49	
Schwarzsee	Weide	3	22	12	1 : 4	10	50	15	1 : 9
1948	Wald	—	50	19		1	10	12	

resp. 1 : 9. Weitaus die größten Unterschiede zwischen Wald und Weide waren also im Emmental festzustellen. Es darf dies aber, gegenüber den beiden anderen Orten, keineswegs als ein Beweis für ein ausgeprägteres unterschiedliches Durchlässigkeitsvermögen zwischen Wald und Weide im Emmental gedeutet werden. Wie schon die beträchtlichen Unterschiede in der Einsickerungszeit vor und nach der Beregnung zeigen ,ist der momentane Wassergehalt des Bodens zur Zeit der Sickerversuche von großer Bedeutung. Im Schwarzsee z. B. wiesen die Böden schon vor der Beregnung einen Wassergehalt von über 90 % der an und für sich sehr hohen Wasserkapazität auf, so daß allein aus diesem Grunde kein so auffallender Unterschied zwischen Wald und Weide zu erwarten war wie im Emmental, wo der geringere Sättigungsgrad sich z. B. in den bedeutend kürzeren Einsickerungszeiten äußert.

Im allgemeinen entspricht, unter vergleichbaren Verhältnissen, einer längeren Einsickerungsdauer auch ein verstärkter Oberflächenabfluß, doch ließ sich auf Grund der bisherigen Versuche keine eindeutige Korrelation zwischen diesen beiden Vorgängen nachweisen.

Das Wasser, das beim Beregnungsversuch nicht wieder als Oberflächenabfluß aufgefangen wird, kann entweder, der Schwerkraft folgend, senkrecht in die Tiefe versickern, im Porenraum des Bodens gespeichert werden, oder aber als Hangwassertrom in tieferen Bodenschichten, mehr oder weniger parallel zur Bodenoberfläche, hangabwärts fließen. Es lag daher nahe, ein größeres Bodenprofil zu öffnen und in tieferen Bodenhorizonten ebenfalls Blechrinnen anzubringen, um so den allfälligen Austritt von Hangwasser zu erfassen. Dabei muß man sich aber darüber im klaren sein, daß durch die Öffnung des Profiles der natürliche Hangwasserfluß gestört wird, da durch die Kapillarspannung der Menisken am offenen Grabenwand eine Stauung entsteht. Der dadurch bewirkte Fehler dürfte um so größer sein, je mehr Feinporen im Boden vorhanden sind.

In Tabelle 4 sind für das Schwarzseegebiet die in 5, 25 und 50 cm Tiefe gemessenen Abflüsse dargestellt, und zwar sowohl beim Wald wie bei der Weide für relativ trockene und relativ feuchte Standorte. Bei beiden Vegetationsarten ergibt sich für die feuchten Partien ein um 30 % höheres Oberflächenabflußprozent als für die relativ trockenen, wobei aber wiederum

die Werte für die Weide bedeutend höher liegen als für den Wald. Verfolgt man die Zunahme des Oberflächenabflußprozentes während der Beregnung, so zeigt sich überall, daß dieses zunächst verhältnismäßig gering ist, dann aber rasch zunimmt und gegen Ende der Beregnung einem gewissen Gleichgewichtszustand zustrebt, der sich wahrscheinlich auch bei fortgesetzter Be-

TABELLE 4

Beregnungsniederschlag und Abfluß in verschiedenen Bodentiefen im Gebiet der Wassermeßstationen beim Schwarzsee (Kt. Freiburg)

Niederschlagssumme in mm oder Liter pro m²	Abfluß in den Bodentiefen von: 0—5 cm		5—25 cm		25—50 cm		0—50 cm	
	Abflußsumme mm oder Liter pro m²	In % der Niederschlagssumme	Abflußsumme mm oder Liter pro m²	In % der Niederschlagssumme	Abflußsumme mm oder Liter pro m²	In % der Niederschlagssumme	Abflußsumme mm oder Liter pro m²	In % der Niederschlagssumme
				Trockener Weidewald				
10	1.1	11	0.1	1	0.0	0	1.2	12
20	2.7	14	0.4	2	0.2	1	3.3	17
40	6.3	16	2.3	6	1.6	4	10.2	26
60	10.0	17	4.8	8	3.7	6	18.5	31
80	12.9	16	7.1	9	6.3	8	26.3	33
100	16.3	16	9.9	10	9.0	9	35.2	35
				Vernäßter Weidewald				
10	1.9	19	1.3	13	0.3	3	3.5	25
20	6.5	33	4.9	24	0.8	4	12.2	61
40	16.2	41	12.1	30	2.0	5	30.3	76
60	26.2	44	19.6	33	3.2	5	49.0	82
80	35.8	45	27.3	34	4.5	6	67.6	85
100	45.7	46	35.1	35	5.9	6	86.7	87
				Trockene Weide				
10	2.8	28	0.0	0	0.0	0	2.8	28
20	8.6	43	0.2	1	0.0	0	8.8	44
40	21.1	53	0.7	2	0.2	0	22.0	55
60	34.3	57	1.3	2	0.5	1	36.1	60
80	48.2	60	1.9	2	0.9	1	51.0	64
100	62.5	62	2.6	3	1.3	1	66.4	66
				Vernäßte Weide				
10	6.9	69	0.1	1	0.0	0	7.0	70
20	15.7	79	0.4	2	0.1	1	16.2	82
40	33.8	85	0.8	2	0.4	1	35.0	88
60	53.6	89	1.4	2	0.7	1	55.7	92
80	73.4	92	2.2	3	1.1	1	76.7	96
100	92.4	92	3.1	3	1.6	2	97.1	97

regnung nicht mehr wesentlich verändert hätte. Diese Feststellung läßt vermuten, daß die Unterschiede, die sich für trockene und vernäßte Standorte im Endabfluß ergeben, nicht nur auf dem verschiedenen Wassergehalt beim Versuchsbeginn beruhen; es dürften dabei vielmehr auch charakteristische Unterschiede im Bodengefüge mitspielen, die aber mit den bisherigen Untersuchungsmethoden nicht genügend erfaßt werden konnten. Daß aber solche Unterschiede bestehen, zeigt sich schon darin, daß bei wassergesättigten Bodenproben aus 0—10 cm Tiefe die Volumenprozente für feste Bestandteile, Wasser und Luft sich bei trockenen Waldpartien wie 33:57:10 verhielten, bei vernäßten Waldpartien dagegen wie 16:76:8. Beim Weideboden ergab sich analog für trockene Partien ein Verhältnis von 40:56:4 und für vernäßte Partien ein solches von 20:76:4.

In den tieferen Bodenhorizonten ist natürlich nur da ein namhafter Abfluß zu erwarten, wo die Oberflächenabflüsse gering sind. In der vernäßten Weidepartie mit 92 % Abfluß in der obersten Rinne ergaben sich aus der Bodenpartie von 5—25 cm Tiefe aber immerhin noch 3 % der Beregnung und aus der Tiefe von 25—50 cm noch 2 %, so daß aus dem ganzen Profil von 0—50 cm Tiefe 97 % des Gesamtniederschlages wieder ausflossen. Beim trokkenen Weidestandort mit 62 % Oberflächenabfluß ergab sich aus den unteren Rinnen ein ähnlicher Zuschuß. Wesentlich größere Bedeutung erlangt dieser unterirdische Zustrom bei den Waldböden. Für den feuchten Standort kommen zum Oberflächenabfluß von 46 % in der Tiefe von 5—25 cm noch volle 35 % hinzu und in der Tiefe von 25—50 cm immer noch 6 %, so daß sich für das gesamte Profil nahezu der doppelte Abfluß ergibt. Es wäre zu erwarten, daß beim trockenen Waldstandort mit nur 16 % Oberflächenabfluß noch mehr Wasser in den tieferen Horizonten austreten würde, was aber keineswegs der Fall war. Allerdings trat auch hier bis zur Tiefe von 50 cm eine Verdoppelung des Oberflächenabflusses ein, womit aber nur ein Gesamtabfluß von 35 % des Niederschlages registriert wurde. Volle 65 % des letzteren sind also gespeichert oder in noch größere Tiefen verfrachtet worden.

Die Entscheidung darüber, ob sich die nicht unbeträchtliche Mehrarbeit für die Anlage mehrerer Meßhorizonte wirklich lohne, wird weitgehend davon abhängen, bis zu welcher Tiefe der Hangwasserstrom noch an den Hochwasserwellen beteiligt ist. Diese Frage dürfte aber keineswegs leicht zu beantworten sein. Ohne Zweifel wird das tatsächlich über die Bodenoberfläche abfließende Wasser das offene Gerinne viel rascher erreichen als jenes, das sich in einer gewissen Tiefe im Boden hangabwärts bewegt. In den behandelten Beispielen im Schwarzseegebiet zeigte sich diese Verzögerung in einer Verspätung des Fließbeginnes an der Grabenwand mit zunehmender Bodentiefe. Die betreffenden Zeiten sind aber sehr stark vom momentanen Benetzungswiderstand abhängig und in den feuchteren Partien auch schwer zu bestimmen, da hier schon vor der Beregnung leichter Bodenschweiß austrat. Bei der trockenen Waldpartie wurde in der obersten Rinne schon nach 1' 30" Abfluß festgestellt, in der mittleren nach 5' und in der untersten erst nach 10' 20". Beim trockenen Weidestandort lauten die entsprechenden Zeiten für den Fließbeginn 4', 12' und 19'. In beiden Fällen handelt es sich also um ziemlich beträchtliche Verzögerungen, die aber doch nicht derart sind, daß nicht auch dieser verlangsamte unterirdische Abfluß bei länger andauernden Starkregen an den Hochwasserspitzen beteiligt sein könnte.

Es dürfte daher angezeigt sein, die Methode der Messung in verschiedenen Bodentiefen weiter auszubauen oder nach neuen Lösungen zu suchen.

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EQUIPEMENT D'UN PETIT BASSIN DE FORET EQUATORIALE EN VUE DE CALCULER SON BILAN HYDROLOGIQUE

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SUMMARY

This note examines the instrumental equipment set on to study the hydrological budget of a small catchment area established in the forest region of Yangambi (Belgian Congo). On this basin, 46 km² wide, are installed fifteen rain gages giving the total amount of precipitation and four recording rain gages to study rainfall intensity.

The water flowing through the river, out of the basin, is gauged by means of a Parshall flume, of eight aperture. This kind of gaging system although not yet much used presents some marked advantages again previous devices like weirs or submerged orifices. These advantages are studied in detail.

RÉSUMÉ

La présente note examine le dispositif mis en place pour l'étude du bilan hydrique d'un petit bassin forestier à Yangambi (Congo Belge).

Sur ce bassin de 46 km² sont installés quinze pluviomètres mesurant la quantité totale de précipitations et quatre pluviographes donnant des chiffres relatifs à l'intensité des précipitations. Le débit de la rivière est mesuré grâce à un mesureur de débit Parshall de huit pieds d'ouverture. Cet appareil relativement récent et encore peu utilisé présente beaucoup d'avantages par rapport aux systèmes de jaugeage classiques. Ces avantages sont étudiés en détail.

INTRODUCTION

L'Institut National pour l'Etude Agronomique du Congo Belge a attaché jusqu'à présent à Yangambi une grande importance à l'étude des processus régissant l'évaporation naturelle et s'est attelé depuis 1950 à résoudre le problème de sa mesure et de son estimation par différentes méthodes toutes basées sur le bilan des échanges énergétiques entre l'atmosphère et les strates évaporantes.

L'évaporation potentielle et actuelle de diverses strates herbacées a été étudiée de près au moyen de cuves lysimétriques analogues à celles utilisées par Thornthwaite et Mather et atteignant les dimensions de 9 m² de surface et 1,50 m de profondeur pour les plus grandes dans lesquelles sont actuellement suivis des caféiers.

Il est certain que cette dimension de 9 m² constitue un maximum qu'il ne convient pas de dépasser sans revoir complètement les méthodes de fabrication.

Il a semblé intéressant, en égard au fait que l'évaporation de diverses strates herbacées mesurée à Yangambi pouvait atteindre des valeurs de 20 ou 30 % supérieures à celle d'une nappe d'eau libre, de chercher à arriver à une estimation du bilan d'eau d'une forêt. La méthode hydrologique appliquée à un petit bassin et étudiée à Yangambi semble devoir conduire à des résultats intéressants.

2. Physiographie du Bassin étudié

Le Bassin de la Loweo est situé à Yangambi à 0° 50' N et 24° 30' E, et à l'altitude moyenne de 450 m.

La région est constituée d'un grand plateau découpé de vallées assez abruptes dont le thalweg se trouve de 20 à 30 m plus bas que le plateau, les sols constituants de ce bassin hydrographique sont des sols sablo-argileux à teneur en argile diminuant suivant le niveau, les sols les plus bas étant les plus sableux.

Le fond des vallées est assez marécageux et le lit de la rivière y serpente d'un côté à l'autre.

Le bassin étudié d'une superficie totale de 46,3 km² est recouvert à concurrence de 82 % par une forêt du type ombrophile typique de la région. Les 18 % restants sont constitués de plantations de palmiers. La longueur du thalweg de la rivière, depuis sa source jusqu'à l'endroit où se fait le jaugeage, est de 9 km.

Cette situation a été choisie à cause des dimensions relativement faibles du bassin-versant, de la facilité de contrôle et du relevé des instruments, de la facilité de la détermination de la surface et de la proximité de la station climatologique de référence mesurant tous les éléments du climat et où sont concentrées toutes les cuves lysimétriques.

3. L'Equipement instrumental du Bassin

Détermination de la surface

Le premier problème est celui de la détermination précise des limites du bassin versant étudié. Compte tenu de la grande homogénéité de texture des sols traversés par la rivière excluant des captages éventuels de sources, par des rivières voisines nous avons choisi comme limite du bassin les lignes de faîte qui l'entourent. Etant donné l'absence de cartes topographiques de la région nous avons dû nous servir de l'examen stéréoscopique de la photographie aérienne au 1/25.000. Ce travail a été ensuite contrôlé par des déterminations de points hauts sur les routes et chemins recoupant les limites du bassin. De cette façon nous sommes arrivés à déterminer sur la carte la surface du bassin. La surface a été planimétrée. On a recherché également les lignes de crête partageant le bassin étudié en deux sous-bassins. Nous ne parlerons pas de l'installation de jaugeage contrôlant le premier sous-bassin celle-ci n'étant pas encore réalisée.

2) Mesure des Précipitations

Quinze pluviomètres dont huit du type « Ministère des Colonies » de 4 dm² d'ouverture et sept du type I.R.M. de 1 dm² d'ouverture ont été installés dans le bassin ou à proximité immédiate. Ces pluviomètres marqués sur le plan d'un cercle sont relevés au moins une fois par semaine. Le chiffre total des précipitations sur le bassin est une moyenne pondérée obtenue en tenant compte de la « représentation » de chaque pluviomètre par la méthode de Thiessen. Dans cette méthode on établit l'aire représentée par le pluviomètre en rejoignant chaque pluviomètre à son voisin par une droite et en élevant les médiatrices sur ces droites. Les surfaces comprises entre les médiatrices donnent les aires cherchées. Les mm de pluies multipliés par les km² de la surface donnent les mètres cubes d'eau tombée sur l'aire partielle considérée au cours de la semaine écoulée. La somme de tous ces chiffres donne les précipitations sur le bassin.

Deux pluviographes Lambrecht à mouvement mensuel seront encore installés dans le bassin à côté de deux pluviomètres existants et contrôlés hebdomadairement.

De plus dans l'étude des intensités, il sera encore tenu compte des renseignements fournis par deux pluviographes Richard situés en dehors du bassin. Les quatre pluviographes sont représentés sur le plan par des carrés.

Notons en passant, que la moyenne pondérée de précipitation obtenue par la méthode de Thiessen ne diffère pas sensiblement de la moyenne arithmétique simple des précipitations, ceci est dû au fait de la densité élevée de pluviomètres soit 1 pour 3 km² en moyenne.

	Thiessen	Moy. Arithmétique
Mars	149.5	146.3
Avril	243.1	231.8
Mai	100.5	101.4
Juin	97.5	99.2
Juillet	118.1	115.4
Août	159.5	155.8
Septembre	213.8	216.2
Octobre	167.1	156.5
Novembre	121.2	114.4
Décembre	127.1	124.4
	1.497	1.461

3) Jaugeage du débit

Etant donné les faibles débits de la rivière à la sortie du bassin étudié (300—400 l/sec) il fut décidé d'y établir un ouvrage de jaugeage donnant d'une façon permanente une relation entre la charge et le débit.

Il fut décidé également de placer l'ouvrage à la place d'un pont en bois sur une route établie sur digue et traversant le thalweg de la rivière. Plusieurs problèmes se posaient quant au choix de l'ouvrage à réaliser :

1) Nécessité d'altérer le moins possible le site par des travaux fort visibles relevant le plan d'eau de la rivière.
2) Danger de relever d'une façon appréciable le niveau de la rivière pour y établir un déversoire ordinaire, la digue n'ayant pas été conçue à l'origine pour reternir l'eau et étant de ce fait peu étanche.
3) Charriage continu de sable par la rivière devant amener un comblement rapide du côté amont du déversoir modifiant ainsi ses caractéristiques.
4) Entraînement lors de coups d'eau de débris végétaux qui pourraient être arrêtés par les bords en mince paroi de déversoirs ou d'orifices submergés.
5) Utilisation si possible d'un seul limnigraphe pour le jaugeage.

Tous ces points interdisaient pratiquement l'emploi de déversoirs, nécessitant 60 cm de hauteur de chute pour obtenir une nappe dénoyée.

Une vanne de fond étant difficilement utilisable du fait des obstructions à craindre et de la nécessité de deux mesures de hauteur d'eau en amont et en aval de l'ouvrage, nous avons utilisé le Déversoir « Parshall Flume » qui apporte une heureuse solution à tous les problèmes énumérés.

Cet appareil est encore peu répandu en Europe et en Afrique. Il utilise le principe du tube de Venturi, dans lequel le fluide est accéléré au travers d'un étranglement. Dans le cas présent la hauteur d'eau dans l'étranglement est proportionnelle au débit.

Ce système présente l'avantage d'accélérer l'eau au passage de l'ouvrage de façon à empêcher les dépôts de sable. De plus le profil de l'ouvrage exempt d'aspérités laisse passer tous les débris végétaux et, enfin, l'ouvrage fonctionne sous une très faible charge.

A Yangambi le déversoir installé fonctionne avec une charge supérieure de 17 cm seulement au niveau de l'ancien cours de la rivière.

Cette hauteur pourrait même être encore moindre tout en assurant un fonctionnement correct du dispositif. La hauteur de charge pour un Parshall Flume n'est que le *quart* de celle qui est nécessaire à un déversoir denoyé pour mesurer le même débit. Le niveau d'eau est mesuré grâce à un limnigraphe Leupold et Stevens type F. mesurant 60 cm de hauteur d'eau sur 30 cm de largeur de diagramme.

4. Perspectives

Bien qu'il soit encore trop tôt actuellement pour publier les résultats des premières mesures, il est cependant déjà possible de dégager certains faits qui ressortent des observations.

Tout d'abord, il est intéressant de constater que le pourcentage d'eau tombée sur le bassin qui percole au limnigraphe est d'environ 20—25 %, la décharge mensuelle variant d'après l'intensité des précipitations et la réserve en eau du sol. Ce chiffre correspond très bien avec d'autres calculs de percolation réalisés pour la totalité du bassin hydrographique du Congo (BERNARD). Il est également intéressant de constater que pour le bassin considéré, la crue consécutive à un orage commence déjà 30 minutes après le début de la pluie pour atteindre son maximum 6 heures après et revenir à un point proche du niveau d'étiage 24 heures après le début de la crue. Le débit maximum observé depuis l'installation du limnigraphe a été de 827 litres/sec, alors que de débit d'étiage varie entre 330 et 360 litres/sec. Ce débit correspondait à une pluie de 29 mm dont les 20 premiers étaient tombés en 45 minutes.

Nous avons pu également constater un fait curieux, observable, pensons-nous uniquement dans des petits bassins. Durant les périodes sèches où le niveau est très bas, on constate que la courbe traduisant les débits a une forme sinusoïdale régulière avec des maxima à midi et des minima à minuit. Il semble que ces fluctuations qui, en débit cumulé, ne représentent que 4—5 % du débit soient dues à l'évapotranspiration de la végétation le long des rives. Ces fluctuations et les pertes de débits constatées sont liées au déficits de saturation moyens de la journée précédente.

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ETUDE HYDROLOGIQUE DE LA RIVIERE LOWEO

Surface du Bassin Supérieur	12.2 Km²
Bassin Inférieur	271 Km²
Bassin Total	46.3 Km²

QUELQUES DONNEES SUR L'ECOULEMENT DANS LES FORETS EQUATORIALES

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RÉSUMÉ

Des études hydrométéorologiques récentes relatives à des bassins versants dont la superficie varie de quelques km² à quelques dizaines de km², ont apporté des données quantitatives nombreuses sur la très forte réduction du ruissellement en forêt équatoriale.

Pour une même averse de l'ordre de 120 mm, à pentes et sols équivalents, la pointe de crue peut être, sous forêt, 8 à 12 fois plus faible que dans les zones de savane des mêmes régions. Le coefficient de ruissellement n'est réduit que dans le rapport de 4 à 6.

L'influence de la perméabilité du sol est beaucoup moins importante qu'en savane. La pente a une action très nette dès qu'elle dépasse 15 à 20 %. Pour des pentes extrêmement fortes, 30 à 50 %, les débits de crues deviennent élevés, plusieurs milliers de l/s. km² pour la crue décennale par exemple.

L'étude des régimes des cours d'eau de la forêt équatoriale n'a été entreprise que très tardivement en Afrique Noire Française. Un seul cours d'eau de cette zone, l'Ogooué (1), a fait l'objet de relevés limnimétriques depuis plus de vingt ans. Quelques stations de jaugeages ont été installées au Cameroun, en 1940, grâce à l'initiative de M. Darnault. L'Electricité de France en a aménagé trois ou quatre en 1948. *Ce n'est guère qu'à partir de 1952* que l'Office de la Recherche Scientifique et Technique Outre-Mer a pu mettre en place un réseau de stations encore bien incomplet, surtout au Gabon.

De même, pour les bassins expérimentaux, les réalisations ont été tardives. La principale raison réside dans la faible importance des débits de crues : ce genre d'étude est moins urgent dans les régions équatoriales que dans les zones sahéliennes à régime torrentiel. Mais, depuis quelques années, le manque d'éléments sur ces crues exceptionnelles en forêt, pour la mise au point des projets d'aménagements hydroélectriques et pour le calcul des débouchés d'ouvrages d'art, a fini par imposer l'étude de bassins expérimentaux de forêt : cinq en Côte d'Ivoire, un au Moyen-Congo, auxquels il convient d'ajouter deux autres bassins hors de l'Afrique Noire : un en Guyane et un autre en Nouvelle-Calédonie.

Les études sur le terrain sont terminées sur un seul de ces bassins expérimentaux, celui de l'Ifou en Côte d'Ivoire. L'interprétation générale est donc à peine commencée.

On doit ajouter, à cet ensemble de données, les relevés climatologiques et, en particulier, pluviométriques des Services météorologiques, relevés qui, généralement, ne sont exploitables qu'à partir de 1950 ou 1951.

Telles sont les bases expérimentales disponibles pour l'analyse de l'écoulement dans ces régions.

(1) Il n'est pas possible de ranger le Congo dans cette catégorie, son bassin versant déborde largement les régions équatoriales et la forêt n'en couvre qu'une partie.

Débits caractéristiques en forêt équatoriale

Bassin	Précipitation annuelle mm	Superficie km²	Module l/s.km²	Crue « décennale » l/s.km²	Etiage l/s.km²
Bia (Côte d'Iv.)	1 475	9 320	8,3	64	0,3
Nyong (Cameroun)	1 460	14 300	8,5	30 (1)	3,9
Lokoundjé (Cameroun)	1 860	1 177	24	185 (2)	3
Lobé (Cameroun)	2 700	1 940	59	280 (2)	10
N'tem (Cameroun)	1 770	18 060	16	42	2,5
M'bali (Oubangui)	1 500	4 905	12	43	4
Likouala Mossaka (M. Congo)	1 600	9 000	17,5	53	6,5
Ogooue (Gabon)	1 800	205 000	25	58	9
Nyanga (M. Congo)	1 800	5 600	37	110	11

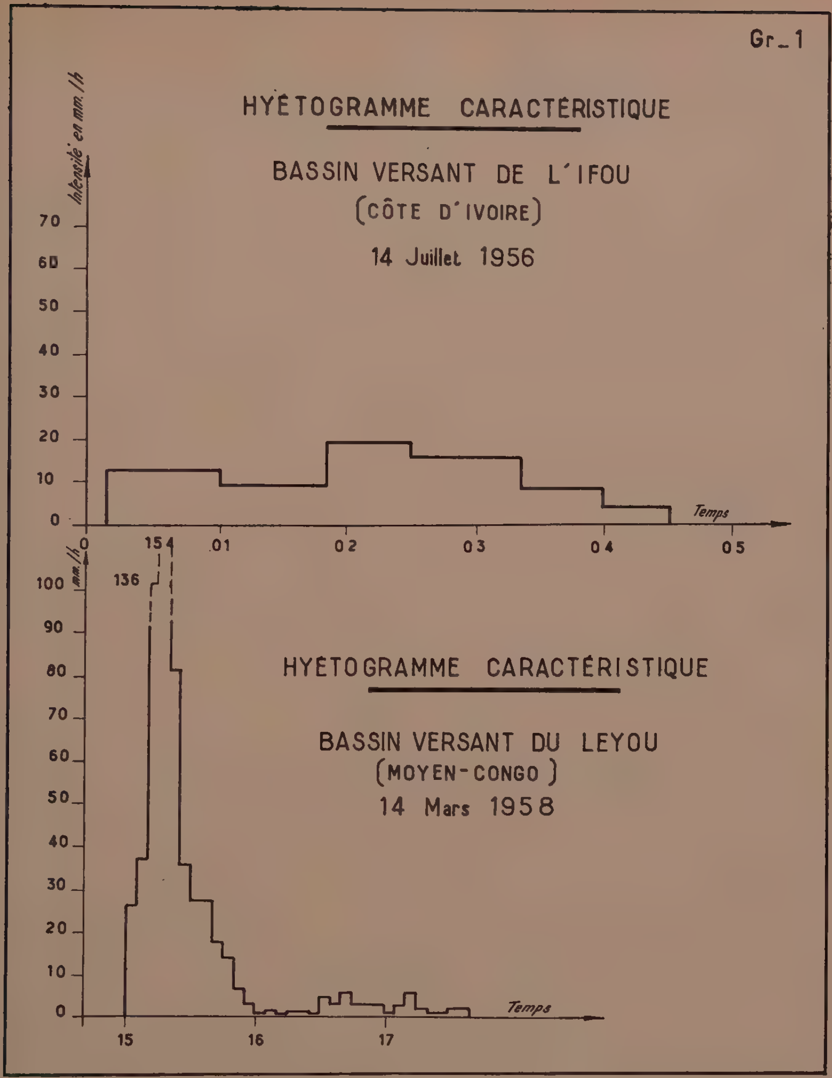
(1) Pertes très importantes dans les plaines d'inondation.
(2) Petits bassins.

I — Étude des Résultats sur Moyens et Grands bassins versants —

Les stations de jaugeage les plus anciennes ont fait l'objet, pour la préparation de l'Annuaire Hydrologique de la France d'Outre-Mer ou pour l'étude du projet de barrage du Kouilou, d'analyses assez poussées portant à la fois sur les courbes d'étalonnage, l'étude critique des relevés bruts et la distribution des débits.

Les régimes ont pu être caractérisés par un certain nombre de chiffres qui, sans présenter une grande précision en raison de la brièveté de la période d'observations, peuvent donner néanmoins une représentation valable.

Rappelons que le régime pluviométrique en régions équatoriales comporte deux saisons des pluies, l'une centrée sur le mois d'Avril ou de Mai, l'autre sur le mois de Novembre ou de Décembre. Deux saisons sèches séparent ces saisons des pluies. Elles sont presque de même importance sous l'équateur thermique, mais dès que l'on s'en écarte, l'une de ces deux saisons s'allonge et devient plus sévère ; la grande saison sèche s'étend de Décembre à Mars dans l'hémisphère boréal, de Juillet à Octobre dans l'hémisphère austral. Les



hauteurs de précipitations moyennes sur les bassins versants observés varient de 1400 à 2500 mm.

On a reporté sur le tableau ci-contre les hauteurs de précipitations moyennes annuelles, la superficie des bassins versants, le débit moyen annuel spécifique, un débit spécifique de crue décennal que nous avons estimé tant bien que mal et enfin le débit spécifique d'étiage.

Les modules varient régulièrement avec la hauteur de précipitation annuelle. Ils diminuent assez rapidement au-dessous de 1600 mm et encore plus rapidement en dessous de 1400 mm comme nous l'avons observé en Côte

d'Ivoire. Cette tendance est due, en grande partie, à la couverture végétale comme l'ont montré les bassins expérimentaux. Un bassin de forêt équatoriale recevant 1200 mm par an présenterait un module spécifique presque nul, alors qu'un bassin de savane soumis aux mêmes précipitations présenterait encore un module de 6 l/s.km² comme c'est le cas, par exemple, de l'Ouémé au Dahomey dont le régime des pluies est presque équatorial et qui reçoit 1225 mm.

L'examen des débits de crue décennale est un peu plus probant. Les bassins de 8000 à 20.000 km² mettent en évidence des débits spécifiques variant de 30 à 65 l/s.km², alors que pour des bassins de savane tropicale tels que les hauts bassins du Sénégal, du Niger, de la Sanaga et du Chari, les débits de crues décennales varient de 65 à 120 l/s.km² pour les mêmes superficies. La différence de débit spécifique est due, en partie, à la concentration de la même hauteur de pluie annuelle en une seule saison, mais cette raison est insuffisante puisque les cours d'eau dahoméens, rares cours d'eau de savane soumis au régime équatorial, présentent des débits spécifiques de crues décennales du même ordre de grandeur : 70 — 80 l/s.km² (1).

Toutes choses étant égales par ailleurs, le volume de crue d'un bassin de savane équatoriale doit donc atteindre au maximum le double de celui d'un bassin de forêt équivalent, pour des superficies supérieures à 4 ou 5.000 km². La différence n'est donc pas très importante et ceci s'explique puisque nous avons pu constater, d'après les études effectuées dans le bassin du Konkouré, que, au Sud de l'isohyète 1200 mm, les crues d'un bassin de quelques milliers de km² étaient dues pour 50 % au débit hypodermique et non pas au ruissellement.

II — Étude des Résultats des Bassins expérimentaux —

Sur des superficies inférieures à 1000 km² et en particulier sur de petits bassins de 5 à 50 km², l'effet régularisateur de la forêt est beaucoup plus net. Le facteur pluviométrique intervenant pour des petits cours d'eau de ce genre est l'averse élémentaire dont nous donnons ci-contre deux diagrammes caractéristiques.

Ces averses donnent naissance à des crues qu'il est facile de comparer aux crues produites sur bassins de savane par les mêmes averses.

Des études systématiques de crues décennales sont en cours en Afrique Noire Française, elles donnent un premier aperçu du ruissellement en forêt : c'est ainsi qu'on a pu noter pour la même superficie de 25 km² et des pentes comparables, de 2 à 8 %, les chiffres figurant sur le tableau ci-après.

Nous laissons volontairement des indications qualitatives pour les pentes et les perméabilités : les études pédologiques et les relevés topographiques n'étant pas terminés pour tous ces bassins. Ajoutons simplement que les pentes du sol sur le bassin de l'Ifou correspondent à des pentes courantes sur les bassins équatoriaux d'Afrique situés sur le vieux socle, alors que les pentes du Loué sont assez exceptionelles pour ces régions de l'Afrique, certains versants dépassant 45°.

Il semble que pour des terrains de pente et de perméabilité courantes, le débit spécifique pour le maximum de la crue décennale atteigne 600 l/s.km².

Pour la savane boisée située plus au Nord, le débit de crue décennale serait dans les mêmes conditions de perméabilité ou de pente de 1000 l/s.km²

(1) Les bassins équatoriaux de savane sont nombreux au Moyen-Congo, mais généralement la perméabilité du sol est nettement anormale.

Nom du bassin	Maximum ponctuel de l'averse mm	Pente	Perméabilité	Débit maximum spécifique
Ifou (Côte d'Iv.)	200	modérée	assez grande	580 l/s.km^2
Leyou (Moyen-Congo)	140	assez forte	modérée	700 l/s.km^2
Nion 1 (Côte d'Iv.)	200	assez forte	modérée	850 l/s.km^2
Nion 2 (Côte d'Iv.)	200	forte	modérée	1500 l/s.km^2
Loué (Côte d'Iv.)	200	très forte	modérée	3 à 4000 l/s.km^2

pour la savane boisée dense, peut-être 1500 à 2000 l/s.km^2 si la savane boisée est plus claire mais pour des averses de *120 à 140 mm au lieu de 140 mm à 200*. Ces chiffres seraient peut-être à majorer de 50 à 100 $^0/_0$ pour des averses de type équatorial (140 à 200 mm). Les bassins de savane donneraient encore des débits plus forts, des débits de crues décennales de 3000 à 6000 l/s.km^2 sont courants par exemple.

Un exemple plus probant est fourni par le bassin expérimental de la Comba situé au Moyen-Congo, comme le Leyou et couvert par une pseudo-steppe.

Soumis à la même averse que le Leyou, il produirait une crue de 6000 à 8000 l/s.km^2. Un second exemple est fourni par la cité africaine de Brazzaville où les pentes sont assez faibles, mais dont le sol est damé par le piétinement, le débit pour la même averse serait du même ordre que ceux de la Comba. On voit donc que le remplacement de la forêt par la savane boisée conduit à multiplier les débits spécifiques de crue décennale par 3 ou 4, et le remplacement de la forêt par la savane ou mieux par la pseudo-steppe conduirait à multiplier par 10 à 12 les débits de crue.

Quelle est l'influence de la pente sur les débits? L'Office de la Recherche Scientifique et Technique Outre-Mer a cherché, en Côte d'Ivoire, à étudier les pentes boisées les plus fortes que l'on puisse trouver en Afrique Occidentale. Les bassins étudiés sont ceux du Nion et surtout du Gboa et du Loué, à proximite de la ville de Man. Les observations n'ont pas été poussées suffisamment longtemps pour qu'il soit possible de donner des chiffres définitifs. Ceux qui figurent au tableau que nous avons vu plus haut doivent être considérés comme de simples ordres de grandeur.

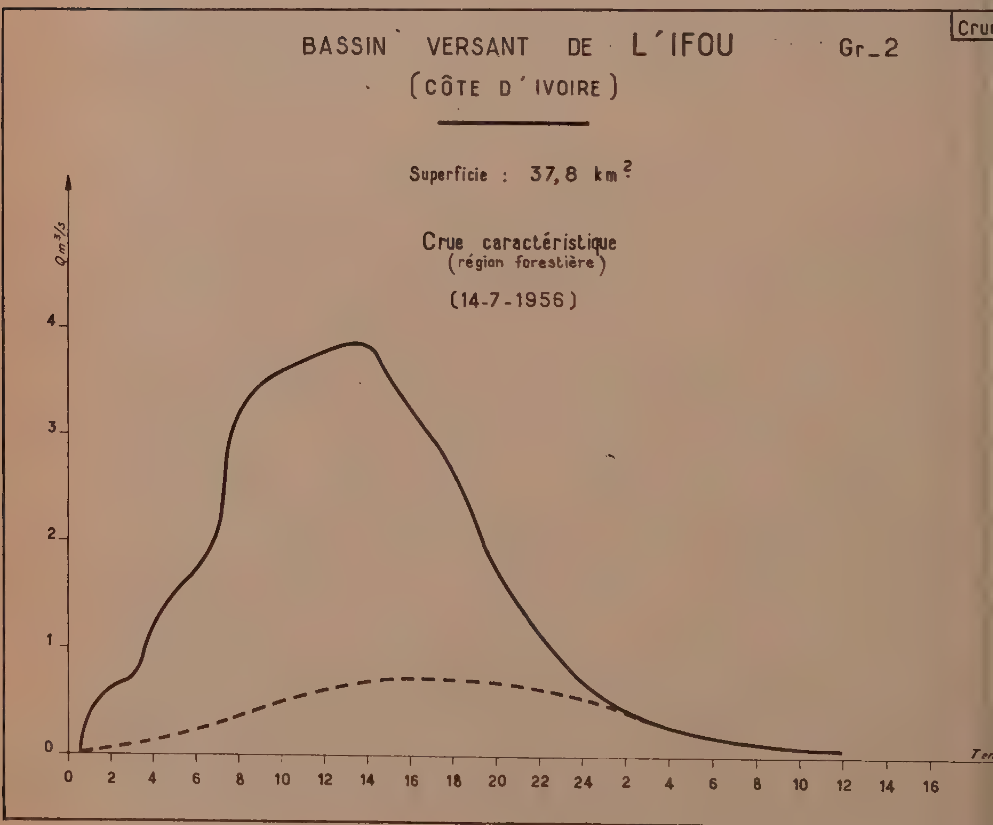
On voit que les débits de crue décennale ne commencent à augmenter que pour des pentes fortes : le bassin du Nion N° 2 présente par endroit des pentes de 20 $^0/_0$. Pour le bassin du Loué dont certaines parties sont inclinées à 100 $^0/_0$, on retrouve des valeurs élevées : de l'ordre de 4.000 l/s.km^2. Cependant, l'influence de la pente est beaucoup moins forte qu'en savane, où le même effet se fait sentir à partir de 5 $^0/_0$ environ au lieu de 10 $^0/_0$. Les débits se rapprochent un peu de ceux observés à l'Île de la Réunion ou la Nouvelle-Calédonie où, pour des pentes analogues, on trouve, en forêt, 10 à 15.000

l/s.km², mais pour des terrains presque saturés avant le début de l'averse et pour des pentes encore plus fortes.

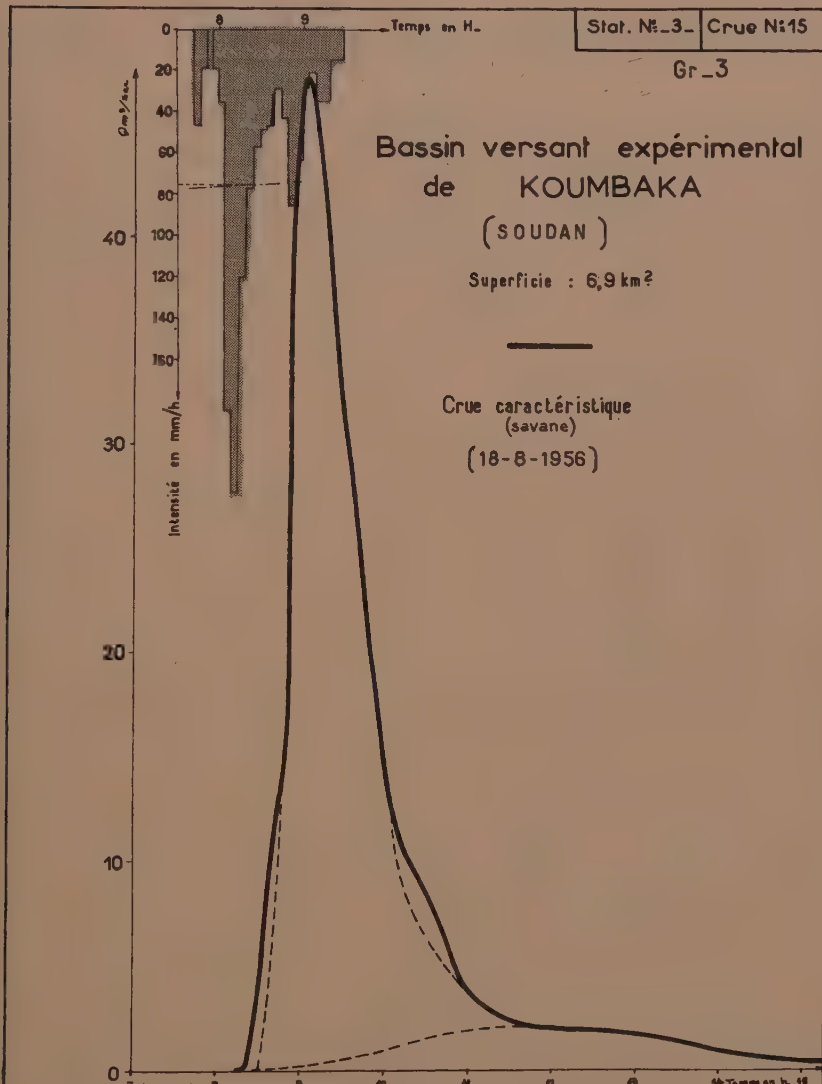
Jusqu'ici, l'influence du sol ne semble pas très marquée, beaucoup moins qu'en savane, par exemple au Moyen Congo où la moindre différence de perméabilité conduit, sur les petits cours d'eau, à des valeurs de crues très différentes comme d'ailleurs on l'observe dans les savanes tropicales au Nord de l'isohyète 700 mm.

Si nous mettons à part le cas des pentés très fortes ou exceptionnelles, on voit que le freniage de la couverture forestière est efficace ; il s'agit bien d'une régularisation, la quantité d'eau mise en réserve étant restituée en partie, de sorte que le coefficient de ruissellement qui mesure le rendement de l'averse est moins affecté que le débit maximum par la couverture forestière. Pour les pentes courantes, il varie sur nos bassins expérimentaux de 10 à 15 % pour la crue décennale, alors qu'en savane, genre pseudo steppe, les chiffres courants sont de 40 à 60 %, ce qui correspond à un rapport de 4, alors que le rapport des débits maxima est de 10.

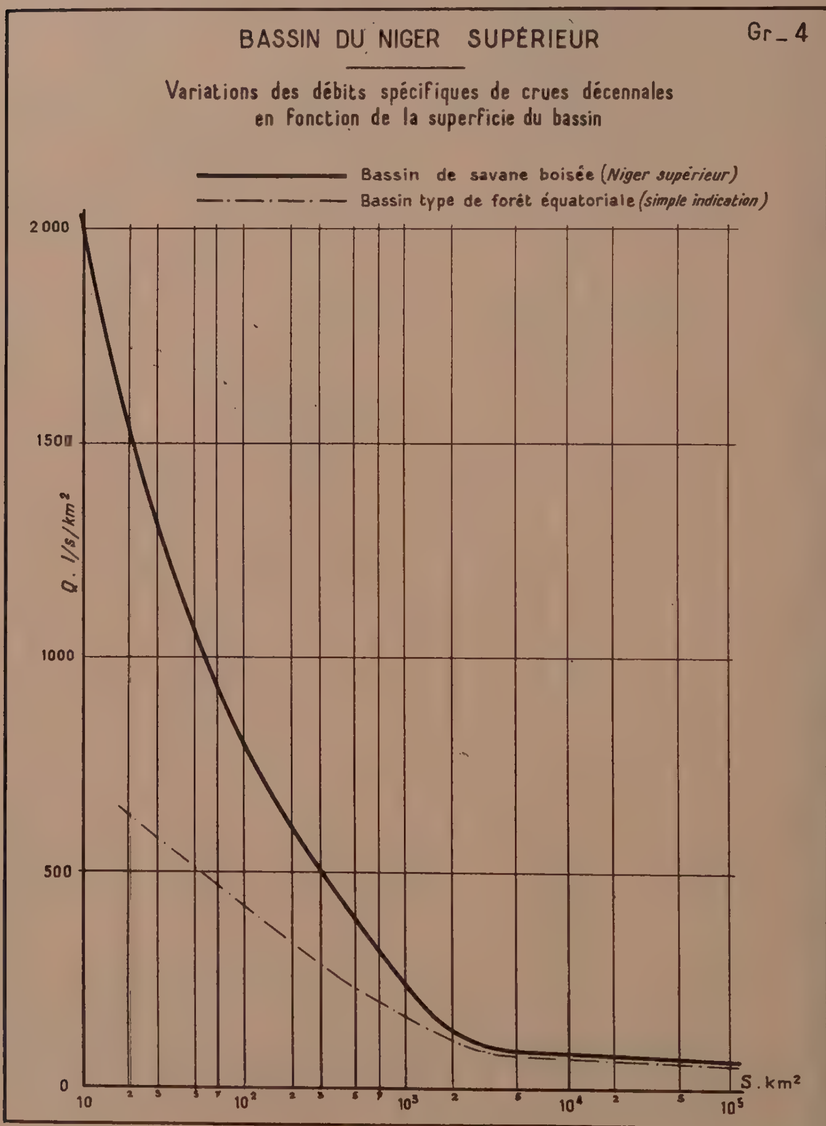
Les graphiques ci-contre montrent l'allure des hydrogrammes de forêt comparés à un hydrogramme de savane.



En général, les bassins de forêt de pente moyenne ou forte donnent, pour une superficie de 25 km², des crues de 15 h. à 25 h. (durée de ruissellement), alors qu'en savane, pour la même superficie, la durée de la crue varie entre 2 h. et 6 h. suivant la pente et la perméabilité du sol. Dans les deux cas, la durée est beaucoup plus longue dès que la pente devient très faible ou que le réseau hydrographique se dégrade.



Pour une fréquence de crue donnée, il est commode de se référer à une courbe idéale représentant les valeurs du débit spécifique de crue de cette fréquence pour des superficies de bassin croissantes, les conditions de sol, de végétation, de pente et de climat restent inchangées. Ceci n'est jamais réalisé au sens strict du mot. Mais, dans certains cas particuliers, par



exemple le Niger supérieur à Koulikoro, les conditions naturelles sont à peu près voisines des conditions théoriques, (sous réserve encore que l'on choisisse les points correspondant aux moyens et aux petits bassins versants de façon à ce qu'ils représentent des caractéristiques moyennes par rapport à la superficie à Koulikoro).

Pour les régions forestières, on peut tracer une telle courbe en choisissant quelques points correspondant à des conditions moyennes, par exemple pour H = 1800 mm et une pente modérée.

Il est intéressant de comparer cette courbe à celle du Niger supérieur qui correspond à un bassin de savane boisée. On constate que l'écart entre débits spécifiques très importants, pour les petits bassins, décroît progressivement pour les grands.

Cette courbe n'est donnée qu'à titre indicatif.

Pour tout ce qui précède, on voit combien nos connaissances sont encore incomplètes et imprécises. Les chiffres que nous avons donnés ne doivent être considérés que comme des ordres de grandeurs car les observations portent à la fois sur des périodes trop courtes et un trop faible nombre de stations de jaugeage et de bassins expérimentaux, mais nous pensons qu'ils peuvent déjà offrir un aperçu sur l'action régulatrice de la forêt équatoriale sur le ruissellement.

THE ELEMENTS OF WATER BALANCE IN THE FOREST AND ON THE FIELD

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SUMMARY

1. For the purpose of determining the hydrological role of the forest it is expedient to conduct an analysis of water-balance elements and the peculiarities of their formation on forested and open plots. It should be noted that determination of each water-balance element is still lacking in precision, which does not permit to solve the problem of the hydrological role of the forest in respect of watersheds as a whole.

2. Total moistening of soils in the forest by rainfall (including precipitation intercepted by trees), horizontal transfer of snow, and condensation is not smaller but often even greater than on the field.

3. Subject to the variety of soil and the conditions of its moistening, moisture-storage in soil and subsoil in the forest may be greater or smaller than on the field.

4. Conditions for the infiltration of melt- and rain-water in the forest are generally much more favourable than on open plots. This indicates more abundant feeding of subsoil waters in the forest. Consequently, more abundant feeding of rivers through subsurface runoff (subsurface runoff = ground water runoff) may be expected on forested watersheds.

5. Available observations data indicate that in summer total evaporation in the forest is generally smaller than on plots under agricultural crops In years of light rainfall the values of total evaporation in the forest and on the field are usually close to each other, while in years of abundant precipitation total evaporation in the forest is considerably lower than on the field.

6. Water-balance calculations for small forested and open plots in various forest zones indicate that in summer total expenditure of moisture on total evaporation (including evaporation of rainfall intercepted by trees in the forest) and subsurface runoff in the forest may be smaller or greater than on open plots.

Comparison of the diffference of precipitation minus runoff on annual basis and for individual seasons shows that total expenditure of moisture on evaporation, subsurface runoff and contribution to watershed moisture-storage is practically the same for small forested and open watersheds.

Available observations data do not permit to isolate with adequate precision subsurface runoff from total moisture expenditure indicated above. However, taking into consideration the observed more abundant feeding of subsoil waters under the forest and higher subsurface runoff from forested plots, there is every reason to conclude that, generally, total evaporation in the forest should be smaller than on the field.

7. The undertaken short survey of water-balance elements for forested and open plots leads to a conclusion that, generally, total (surface and subsurface) runoff from forested plots and watersheds should be higher than that from open (field) plots and watersheds.

RÉSUMÉ

1. Dans l'intention de déterminer le rôle hydrologique de la forêt il est nécessaire de faire analyse des éléments du bilan hydrologique et des particularités de leur formation dans des parcelles couvertes d'une part de forêt et d'autre part de culture.

Il est à noter que la détermination de chacun de ces éléments manque encore de précision ce qui ne permet pas de donner une solution au problème du rôle hydrologique de la forêt.

2. L'alimentation en eau des sols de la forêt par la pluie (y compris les précipitations interceptées par les arbres), par transport horizontal de neige

et par condensation n'est pas moindre en forêt que dans les champs cultivés et elle est même souvent plus grande.

3. Par suite de la variété des sols et des conditions de leur humidification, la teneur en humidité du sol et du sous-sol dans la forêt peut être ou supérieure ou inférieure à ce qu'elle est en pleine campagne.

4. Les conditions d'infiltration de l'eau de pluie ou de fusion dans la forêt sont généralement plus favorables qu'en pleine campagne.

Ceci conduit à une alimentation plus abondante en eau du sol de la forêt.

Par conséquent, une alimentation plus abondante des rivières par l'eau souterraine doit être attendue en forêt.

5. Les résultats des observations disponibles indiquent qu'en été l'infiltration totale de la forêt est généralement plus faible qu'en pleine campagne.

Dans les années de faible précipitation la valeur de l'évaporation totale dans la forêt et en pleine campagne est habituellement très proche l'une de l'autre, tandis que dans les années de précipitation abondante l'évaporation totale de la forêt est considérablement plus faible qu'en pleine campagne.

6. Les calculs de bilan d'eau pour de petites parcelles forestières et de pleine campagne dans des zones forestières indiquent que la dépense totale d'humidité en été pour l'évaporation totale (en y comprenant l'évaporation de la pluie interceptée par les arbres dans la forêt) et l'écoulement souterrain dans la forêt peut être inférieure ou supérieure à celle des parcelles en pleine campagne.

La comparaison de la différence des précipitations moins écoulement sur des bases annuelles et pour les saisons particulières montre que la dépense totale en humidité pour l'évaporation, l'écoulement souterrain et la participation à l'emmagasinement d'humidité dans la forêt est pratiquement la même pour les petites parcelles forestières ou de pleine campagne. Les observations disponibles ne permettent pas d'isoler avec une précision suffisante l'écoulement souterrain de la dépense totale d'humidité dont il est question ci-dessus.

Cependant, prenant en considération l'alimentation plus abondante souvent observée des eaux souterraines sous la forêt et l'écoulement souterrain plus élevé des parcelles forestières, il y a raison de conclure que généralement l'évaporation en pleine forêt devrait être plus petite qu'en pleine campagne.

7. Les observations entreprises pour la détermination des éléments du bilan d'eau dans des parcelles forestières et de pleine campagne conduisent à la conclusion que, généralement, l'écoulement total (superficiel et souterrain) des parcelles forestières devrait être plus élevé que celui des parcelles en pleine campagne.

For the purpose of determining the hydrological role of the forest it is expedient to conduct an analysis of water-balance elements and the peculiarities of their formation on forested and open plots.

Assuming that surface and subsurface water from the adjoining area does not reach the plots under study or small watersheds, while condensation of moisture is small, the water-balance equation assumes the following form

$$x = y + y_1 + z \pm \triangle w \pm \triangle u,$$

where x is precipitation; y and y_1 are surface and subsurface runoff, respectively; z is total evaporation, w is variation of moisture-storage in soils; u is variation of ground-water storage. All these elements are expressed in millimeters of water depth.

It should be noted that determination of each water-balance element is still lacking in precision, which does not permit to solve the problem of the hydrological role of the forest in respect of watersheds as a whole.

1. Precipitation (x)

Analysis of precipitation in the forest and on the field indicates that raingauge-measured annual precipitation on glades is generally 8 to 20 per

cent higher than on open (unforested) plots. This difference is largely accounted for by the escape of some portion of precipitation from raingauges on open plots. In a number of instances, however, there seems to be an actual increase in precipitation in large tracts of forest.

In the forest, on its edge in particular, there is also a supply of moisture in the form of condensation (about 10 per cent of annual rainfall) and accumulation of snow carried by the wind (comprising snow storage two to four times greater than on open level fields) unrecorded by raingauges.

Along with the observed increase in precipitation in the forest, some portion of rainfall is intercepted by trees. This interception amounts, on the average, to 6-9 per cent of annual rainfall in deciduous forests, 15 per cent in pine forests, and 20-33 per cent in fir forests. In rains with a considerable depth of precipitation and high intensity this interception almost does not occur (amounting on the average to 1-2 mm per rain).

However, not all precipitation intercepted by trees is lost by useless evaporation. With strong winds as well as at the time of snow melting some of intercepted precipitation reaches the soil under the trees, while intercepted summer precipitation evidently contributes to lower transpiration (1).

Of decisive importance in runoff formation is such precipitation that intensely moistens the soil (snow-melting period, heavy rainstorms and abundant autumn rains).

Light rains (largely intercepted by trees) slightly moisten the soil and soon evaporate, taking almost no part in runoff formation either on the field or in the forest.

As indicated by calculations, total moistening of soils in the forest is not smaller, but often even greater than on the field.

2. Moisture-storage in soil and subsoil (w) and ground waters (u)

Conditions for the infiltration of melt- and rain-water in the forest are generally much more favourable than on open plots. Thus, on the small watersheds of the Nizhnedevitzkaya Runoff Station the 3-year average amount of infiltration in the spring period was 64 mm on the field and 151 mm in the forest. According to the data of the Kamennostepnaya Observatory, infiltration in spring in forest shelter belts of high snow-accumulation may reach 400 to 700 mm and over, infiltration on the field being of the order of 40 to 60 mm (2).

Subject to the variety of soil, conditions of its moistening, and depth of ground water, moisture-storage in soil and subsoil in the forest may be greater or smaller than on the field.

Greater infiltration of melt- and rain-water in the forest generally results in more abundant feeding of ground waters under the forest as compared to similar open plots.

3. Surface runoff in the forest and on the field ($\overline{\overline{y}}$)

Surface (slope) runoff in the forest is, as a rule, several times smaller than on open (unforested) plots. A typical example in this respect is provided by observations on open and forested runoff plots of the Kamennostepnaya Observatory as given in Table 1.

TABLE 1

Snow-storage (x), runoff depth (y)

and runoff coefficient ($\frac{y}{x}$) for the spring period (mm)

Plot	1952			1953			1954			1955		
	x	$\bar{\bar{y}}$	$\frac{\bar{\bar{y}}}{x}$	x	$\bar{\bar{y}}$	$\frac{\bar{\bar{y}}}{x}$	x	$\bar{\bar{y}}$	$\frac{\bar{\bar{y}}}{x}$	x	$\bar{\bar{y}}$	$\frac{\bar{\bar{y}}}{x}$
Open	89	69	0.77	112	66	0.59	45	3.6	0.08	28	27.5	0.98*
Forested	94	5	0.05	106	4	0.04	60	0.9	0.015	70	64	0.92*

* After two very intense winter thaws.

The foregoing data indicate that slope runoff in the forest is generally insignificant.

In view of the above, smaller runoff should be expected from small forested watersheds, which is fully corroborated by actual observations (2).

4. Evaporation in the forest and on the field (z)

Comparison of total evaporation values in the forest and on the field based on numerous data published by Soviet and foreign authors indicates that total evaporation in the forest (including that of rainfall intercepted by trees) may be smaller or greater than on field plots (2). This is corroborated by observations of evaporation in summer at the Valdai Hydrological Scientific Research Laboratory of the State Hydrological Institute. Observations were conducted by means of weighing and hydraulic evaporimeters to determine total evaporation from young trees (birch, pine, fir of 12 to 22 years), agricultural crops (meadow, clover, flax, oats, winter rye, maize, potatoes) and fallow field. The four-year average amounts of evaporation and precipitation are given in Table 2.

The data obtained indicate that, on the average, total evaporation in a young forest in summer is smaller than on the field.

Such comparison of total evaporation values for the forest and agricultural fields does not certainly solve the problem of the hydrological role of the forest, yet it makes one more cautious with regard to conclusions as to allegedly greater total evaporation in the forest than on the fields.

TABLE 2

	Young trees	Agricultural crops	Fallow field
Precipitation mm	346	309	309
Evaporation mm	237—266	282—338	250

TABLE 3

Watershed	Watershed area sq.km.	Forest cover pct	x	y	x-y
Priusadebny Ravine	0.36	0	705	304	401
Usadievsky Ravine	2.67	6	675	395	280
Elovy Ravine	0.0023	100	801	350	451
Taezhny Ravine	0.45	98	824	270	554
River Polomet	630	60	762	399	363

5. The principal elements of water balance for small watersheds

It is undoubtedly interesting to compare the principal water-balance elements for small open and forested watersheds representative of the area under study.

For such comparison, data were used for open and forested watersheds of the Valdai Hydrological Laboratory, viz., Priusadebny, Usadievsky, Elovy and Taezhny Ravines (*) as well as the Polomet River.

It will be seen from the data in Table 3 that raingauge-measured annual precipitation on the average amounted to 690 mm. on open watersheds, 812 mm. on forested watersheds, and 762 mm. in the Polomet River Basin. Measured precipitation over open watersheds is on the average 15 per cent smaller than on forested ones.

Annual runoff on open Priusadebny Ravine is greater than on forested Taezhny Ravine and smaller than on forested Elovy Ravine. Runoff on open Usadievsky Ravine is greater than on both forested ravines. At the same time, runoff on the Polomet River with 60 per cent of its watershed area under forest is greater than on any of the small watersheds. On small forested and open watersheds, differences in annual runoff values are mainly due to hydrogeological conditions and to the extent of ground-water drainage. Analysis of precipitation and runoff data for all years of observations permits a conclusion that annual unrecorded subsurface runoff on the small watersheds of the Valdai Hydrological Laboratory is, on the average, some 70-80 mm. smaller than on the Polomet River.

In addition to the data of the Valdai Hydrological Laboratory, observation records of other runoff stations of the Main Administration of Hydrometeorological Service of the U.S.S.R. were also subjected to analysis. Some results of the analysis of observations on small watersheds of the Buchanskaya Runoff Station (near Kiev) and the Bolshoe Sareevo Runoff Station (near Moscow) are outlined below.

For the Buchanskaya Runoff Station characterized by slightly divided relief and slightly podzolized turf soils, three small watersheds were considered. They are: the Gorlianka River with watershed area of 34.4 sq.km.

(*) small watersheds of creeks.

30 per cent of which is under forest, Grebelka creek with watershed area of 8.3 sq.km. 72 per cent of which is forested, and Toporetz Creek with watershed area of 5.6 sq.km. entirely open. Erosion channel depth of all three watersheds is practically the same.

For the Bolshoe Sareevo Runoff Station characterized by moraine-erosion slightly undulating relief with podzol soils, four watersheds were examined: Dushiletz Creek with watershed area of 6.2 sq.km. 71 per cent of which is under forest, Lyzlovo Ravine with watershed area of 1.84 sq.km. 11 per cent of which is forested, and Progony Creek with watershed area of 0.8 sq.km. 45 per cent of which is under forest. All the three watercourses have an approximately equal depth of erosion channel. The Medvenka River with watershed area of 21.5 sq.km., 45 per cent of which is under forest, has a deeper erosion channel.

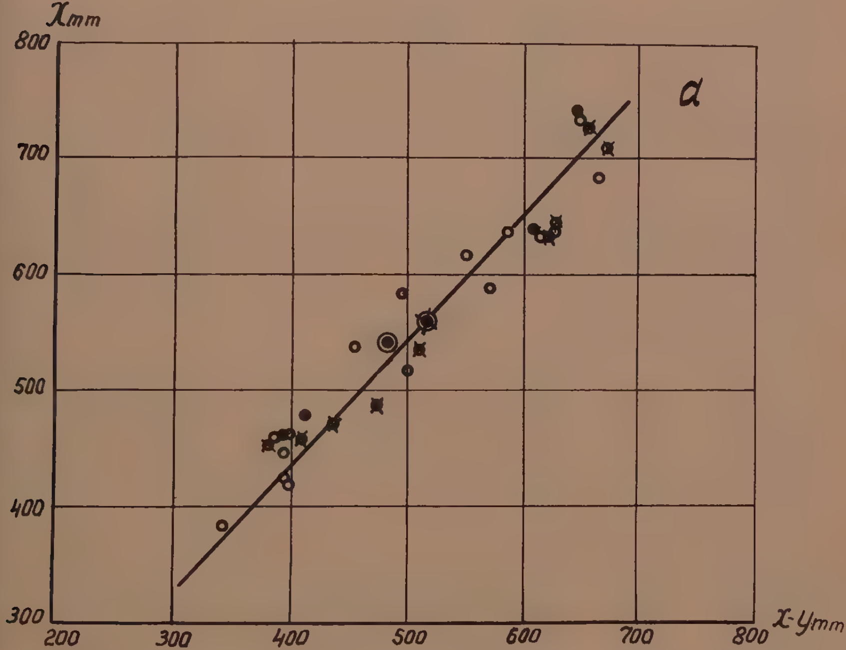


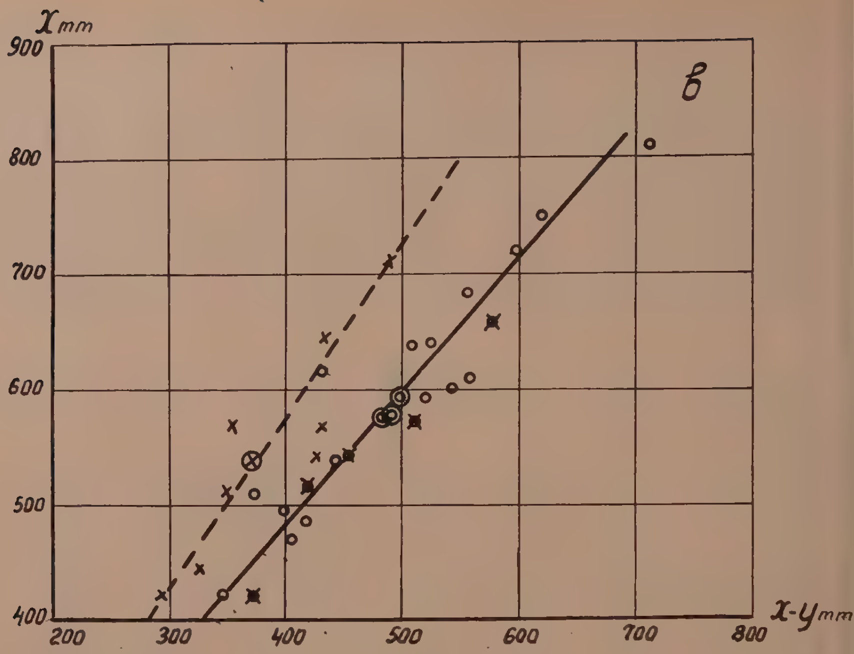
Fig. 1 Relationship between annual precipitation (x) and the difference of precipitation minus runoff (x—y) mm. for small watersheds.

(a) Buchanskaya Runoff Station

● Gorlianka River F = 34.4 sq.km., ß = 30 %;

⊠ Toporetz Creek F = 5.6 sq.km., ß = 0 %;

○ Grebelka Creek F = 8.3 sq.km., ß = 72 %;



(b) Bolshoe Sareevo Runoff Station

● Dushiletz Creek F = 6.2 sq.km., ß = 71 %;

⊗ Lyzlovo Ravine F = 1.8 sq.km., ß = 11 %;

○ Progony Creek F = 0.8 sq.km., ß = 45 %;

⊠ Medvenka River F = 21.5 sq.km., ß = 45 %;

Annual precipitation (x), runoff (y) and the difference (x—y) have been determined for all these watersheds. Graphic comparisons of relationship (x—y) = f(x) are given in Fig. 1 (a, b). These relationships indicate that for the watersheds of the Buchanskaya Runoff Station (Fig. 1a) the value (x—y), which on the whole characterizes total evaporation from watershed, is almost entirely determined by the amount of annual rainfall, and is independent of the extent of watershed forest cover. A similar conclusion may also be drawn in respect of the three small watersheds of the Bolshoe Sareevo Runoff Station (Fig. 1b). For the Medvenka River which has a deeper erosion channel and a forest cover of 45 per cent, the pattern of relationship remains the same, although the value (x—y) is substantially lower. This

difference is due to a greater ground water drainage amounting to some 60 to 100 mm. annually. The foregoing data fully corroborate the conclusions arrived at in respect of the watersheds of the Valdai Hydrological Laboratory.

Comparisons similar to those outlined above but covering individual seasons may also be useful in ascertaining the hydrological role of the forest. Such comparisons on the four-year average basis for Usadievsky and Taezhny Ravines for spring, summer and autumn are given in Table 4. Precipitation figures (x) for spring include data obtained by snow-measurements made by the beginning of spring snow-melting plus precipitation in the spring runoff period.

TABLE 4

Four-year average amounts of precipitation (x), runoff (y) and the difference (x—y) for individual seasons in mm.

Watersheds	Forest cover per-centage (ß %)	Spring (March—May)			Summer (June—Sept.)			Autumn (Oct.—Dec.)		
		x	y	x—y	x	y	x—y	x	y	x—y
Usadievsky R.	6	308	218	90	265	68	197	168	88	80
Taezhny R.	98	320	165	155	318	65	253	182	40	142
Difference	—	—12	+53	—65	—53	+3	—56	—14	+48	—62

No data is given for winter as there is only snow-accumulation but no runoff on small ravines.

Analysis of values given in Table 4 permits the following conclusions:

(1) Maximum snow-accumulations on the open and forested watersheds, on the four-year average basis, are practically equal.

(2) Spring and autumn runoff from the open watershed is higher than from the forested one, summer runoff is practically the same for both watersheds.

(3) The difference precipitation minus runoff (x—y) for the open watershed is for all seasons smaller than for the forested one. On the average, this difference for the open watershed is smaller than for the forested one by 65 mm. for spring, 56 mm. for summer and 62 mm. for autumn.

The comparative stability of the value of difference (x—y) for various seasons indicates that this difference is due not to higher total evaporation from the forested watershed but to other physico-geographical peculiarities of the watersheds. In our opinion it is accounted for by higher subsurface runoff from the forested watershed.

Let us now make a similar comparison for the experimental Swiss watersheds Sperbel and Rappen.

TABLE 5

Season	Sperbel Ravine			Rappen Ravine		
	Precipitation (x) mm.	Runoff (y) mm.	(x—y) mm.	Precipitation (x) mm.	Runoff (y) mm.	(x—y) mm.
Autumn (Sept.—Nov.)	378	154	224	401	216	185
Winter (Dec.—Feb.)	329	152	177	350	190	160
Spring (Mar.—May)	403	261	142	418	349	69
Summer (June—Aug.)	523	205	318	533	251	282

The principal water-balance elements through 25 years of observations for Sperbel Ravine with watershed area of 0.56 sq.km., 98—99 per cent of which is under forest, and Rappen Ravine with watershed area of 0.7 sq.km., 31—33 per cent of which is forested, according to H. Burger (5), are given in Table 5.

For Rappen Ravine the value of (x—y) for all seasons is smaller than for Sperbel Ravine.

The relationship of (x—y) = f(x) for different seasons is shown in Fig. 2 from which it follows that for autumn, winter and summer this relationship is similar to those shown in Fig. 1. The only exception is the spring period which is distinctly different from the other seasons as concerns the conditions of runoff formation.

The parallel course of the relationship of (x—y) = f(x) for autumn, winter and summer for both ravines indicates that total expenditure of moisture on evaporation, subsurface runoff and contribution to watershed moisture-storage does not depend on the extent of watershed forest cover.

On the basis of an analysis of the data outlined above, similar conclusions were also arrived at by D. L. Sokolovsky (3).

Conclusion

(1) Analysis of water-balance elements on forested and open plots and small watersheds leads to a conclusion that total evaporation in the forest, as a rule, is not higher but lower than on open agricultural fields.

(2) The wide-spread view as to high total evaporation in the forest everywhere, and the drying up effect of the forest on plains does not correspond to the facts.

(3) Subsurface runoff from forested sections of watersheds should be higher than from open plots.

(4) With a view to an ultimate solution of the problem, every measure should be taken to improve the methods of direct determination of all water-balance elements in respect of small forested and open plots as well as watersheds as a whole.

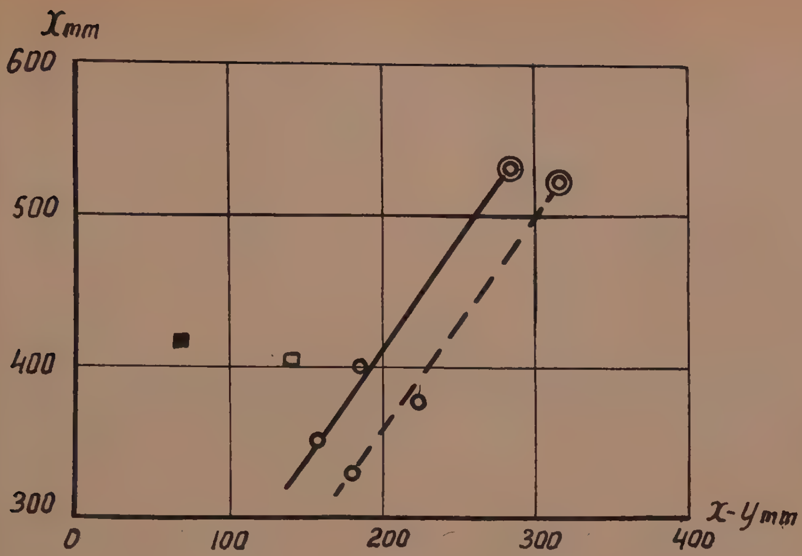


Fig. 2 Relationship between mean long-term seasonal amounts of precipitation (x) and the difference of precipitation minus runoff (x—y) for two ravines in Switzerland.

	Autumn	Winter	Spring	Summer
Rappen Ravine	⊗	●	■	◉
Sperbel Ravine	⊗	○	□	◎

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THE FOREST AND THE RIVER RUNOFF

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SUMMARY

1. The problem of the hydrological role of the forest is of great scientific and practical importance. Though age-old, this problem remains unsolved.

The effect of the forest on surface and subsurface runoff manifests itself in different ways, which renders more difficult the investigation of the problem.

2. All available observations data generally indicate a considerably lower spring, summer and annual runoff on small forested watersheds, as compared with similar open (i. e. unforested) watersheds, the reason being more favourable conditions for the infiltration of melt- and rain-water into loose forest soil and the resultant sharp decrease in surface runoff in the forest.

3. The results obtained by a number of investigators (D. L. Sokolovsky, V. V. Rakhmanov, A. P. Bochkov, L. M. Sidorkina and others) indicate that annual runoff for medium rivers is generally greater from more forested river-basins than from less forested or open watersheds.

4. It has been established by the writer's research that on rivers with watershed area of 1000 sq km and over, longterm mean values of annual runoff (y_0) are in close relationship with long-term mean annual precipitation (x_0) and the river-basins' forest cover percentage (β %). These relationships — $y_0 = f(x_0, \beta)$ — reflect a consistent increase in mean annual runoff with heavier precipitation and greater watershed forest cover. Total increase in river runoff under the influence of the forest may reach 50 to 60 per cent as compared to runoff from similar unforested watersheds.

The presence of forest on watersheds (of 1000 sq km and over in area) usually promotes stable subsurface feeding of rivers which with favourable hydrogeological conditions may increase two to four times under the influence of the forest. On forested watersheds, floods and high water usually have a more smooth course, their duration increases, while peak discharges are, as a rule, somewhat lower.

5. Analysis of values close to annual evaporation (x-y), determined by subtracting runoff (y) from precipitation (x), for water-years (October-September) showed a satisfactory relationship between the values (x-y) and precipitation $(x\text{-}y) = f(x)$.

It was found at the same time that the value (x-y) characterizing total evaporation (basin's accumulation included) for most river-basins, with annual precipitation of as much as 400 mm, depends only on precipitation and not on watershed forest cover. With precipitation of over 400 mm there is a trend toward smaller total evaporation value (x-y) as the extent of the river-basins' forest cover progresses.

6. Runoff in years of high water-supply accounts for 40 to 70 per cent of the mean long-term river runoff formation in the U.S.S.R. in Europe.

In the light of the above, an explanation suggests itself of the discovered increase in mean long-term annual runoff in connection with greater watershed forest cover [$y_0 = f(x_0 \beta)$]. Calculations based on the variations of the values $x\text{-}y = f(x)$ indicated above show that for a forested river-basin ($\beta = 100$ %) a mean long-term annual runoff should be about 60 per cent greater than that from a similar open (unforested) river-basin. Thus, calculated evaporation agrees with the data obtained by the curves $y_0 = f(x \beta)$.

7. It should be noted in conclusion that, under the influence of the forest, runoff, as a rule, decreases on small watersheds and increases on medium and large rivers.

RÉSUMÉ

Cette question est difficile à résoudre du fait des multiples influences de la forêt. Tous les résultats d'observation indiquent des écoulements de printemps, d'été et total pour les petits bassins forestiers inférieurs à celui des aires découvertes par suite des meilleures conditions d'infiltration en forêt.

Pour les bassins moyens, l'écoulement semble être supérieur dans le cas d'une couverture forestière.

Les recherches de l'auteur lui permettent d'assurer que pour des bassins d'étendue supérieure à 1.000 km², les valeurs moyennes de l'écoulement annuel sont une fonction croissante de la hauteur des précipitations et de l'étendue du bassin et qu'une couverture forestière peut provoquer un accroissement de 50 à 60 % de l'écoulement. Cet écoulement y est d'ailleurs plus stable, la forêt réduisant les sommets des crues en allongeant ces dernières.

Les valeurs de l'évaporation obtenues par la différence entre les précipitations et l'écoulement montrent que pour les valeurs des précipitations annuelles inférieures à 400 mm, la valeur de l'évaporation est indépendante du degré de couverture forestière mais que par contre l'évaporation est plus faible quand la couverture forestière augmente pour les précipitations annuelles supérieures à 400 mm.

The determination of the hydrological role of the forest is of great scientific and practical importance for sylviculture, water conservation and forest amelioration measures as well as for hydrological calculations. Though age-old, this problem has not, as yet, been solved. The reasons for it lie in the difficulties of determining the role of individual physico-geographical factors (the forest included) in runoff formation as well as in the lack of reliable methods of investigation.

The inadequacy of the methods employed in measuring elements of the water balance, for forest conditions in particular, and the determination of some of those elements by subtraction (i.e. as the remainder of the water balance equation) lead to unreliable and often wrong ultimate conclusions as to the hydrological role of the forest. This is particularly conspicuous when results of insufficiently reliable observations and calculations for small watersheds or limited areas are applied to river-basins.

THE EFFECT OF THE FOREST ON RUNOFF FROM SMALL WATERSHEDS

There is no doubt that a considerable decrease in spring and annual runoff from forested watershed-lands takes place on small watersheds and runoff-plots, the reason being very favourable conditions for the infiltration of melt- and rain-water into the loose forest soil.

Subject to the hydrogeological conditions and the depth of the erosion channel of small watercourses, the depth of runoff from forested watersheds as compared to that from similar neighbouring unforested small watersheds may vary within a very wide range, amounting to 0.1-0.5 of the runoff from small open watersheds and slopes in the steppe and forest-steppe zones and to 0.5-1.0 in the forest zone (Fig. 1).

In spite of the wide range of variations of the runoff from small watersheds under the influence of the forest, the considerable amount of accumulated observations data permits to draw some general conclusions.

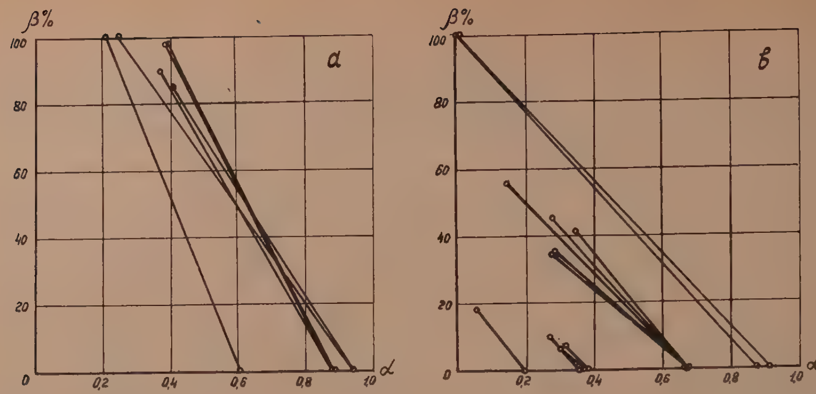

Fig. 1 Dependence of spring runoff coefficients (α) for small watersheds on their forest cover (β %).
(a) the forest zone; (b) the steppe and forest-steppe zone.

It has been established that on the long-term average the decrease of the runoff coefficients (α) for small watersheds owing to their forest cover area (β %) in the U.S.S.R. in Europe may be expressed by the following correlations:

	Spring runoff coefficient	Annual runoff coefficient
Steppe and forest-steppe zone	$\alpha_f = \alpha_o - 0.009\ (\beta_f - \beta_o)$	$\alpha_f = \alpha_o - 0.003\ (\beta_f - \beta_o)$
Forest zone	$\alpha_f = \alpha_o - 0.005\ (\beta_f - \beta_o)$	$\alpha_f = \alpha_o - 0.002\ (\beta_f - \beta_o)$

where α_f is runoff coefficient for completely or partly forested small watersheds;
α_o is runoff coefficient of open or less forested small watersheds;
β_f and β_o is forest cover of the corresponding watersheds in terms of per cent.

In certain cases, however, there are considerable departures from the relationship indicated above. Thus, at a time of very intensive downpours a considerable purely surface (slope) runoff may be observed in the forest as well.

Comparison of the values of the runoff depth or coefficients for small watersheds with varying degrees of forest cover usually serves as a basis for conclusions as to a considerable decrease of river runoff under the influence of the forest.

However, it would be wrong to draw conclusions as to the hydrological role of the forest with respect to medium and large rivers on the basis of hydrological observations on small watersheds as small watercourses generally drain a smaller number of aquifers than medium or large rivers, thus accounting only for some part of subsurface flow.

Attempts to determine the hydrological role of the forest by solving the water-balance equation for individual open and forested plots and small watersheds have, so far, failed to achieve a reliable solution of the problem. Therefore, without relaxing efforts to improve methods of determining all water-balance elements by means of direct measurement, it is necessary to employ other procedures in solving the problem in question. In our opinion, nowadays in determining the role of the forest in river-runoff formation it is expedient to investigate the relationships between river-runoff values for medium rivers with watersheds of varying forest cover, with due regard to other physico-geographical conditions.

The Effect of the Forest on River Runoff

When comparing annual runoff both for individual years and for a long-term period for medium rivers lying in similar physico-geographical conditions, a number of authors (D. L. Sokolovsky (4,5), V. V. Rakhmanov (2), A. P. Bochkov (1), L. M. Sidorkina (3) and others) noted that annual runoff for more forested river-basins is generally greater than from less forested and open watersheds. At the same time there is a consistent relationship between the depth of annual runoff and the basins forest cover percentage.

River runoff is an integral result of the interaction of numerous factors of which precipitation and evaporation are, naturally, the most important. This should also be taken into account in determining the effect of the forest on runoff.

In analysing the hydrological role of the forest in respect of medium rivers, the author used data on long-term mean values of annual runoff, precipitation (with relationships between liquid and solid phases), air temperatures, relative humidity and saturation deficit of air, radiation balance, as well as on watersheds'forest cover percentage, the geographical location of the watersheds, their relief, the geological and soil conditions, lacustrine characteristics, etc. Data on more than 200 river-basins of the U.S.S.R. in Europe with watershed areas of over 1000 sq.km. were made use of in the investigation, piedmont and carst rivers as well as rivers with a developed lake system being excluded from further study.

The results of the investigation showed that the above hydrometeorological and other physico-geographical factors have a well-defined latitudinal-zone character. This makes it much more difficult to determine the role of individual factors in river runoff formation.

For the area under consideration, the best relationships are obtained between long-term mean annual runoff (y_0) and the river-basins'forest cover percentage (β %), with a given mean annual precipitation (x_0). A specimen of the relationships indicated $y_0 = f(x_1 \beta)$ for river watersheds of mean annual precipitation of 625 mm and 550 mm (with winter precipitation amounting to no less than 18-20 % of the annual value)—is given in Fig. 2 (a, b). These relationships indicate a consistent augmentation of the mean annual river runoff with increasing precipitation and forest-cover area of watersheds. As compared to entirely open basins ($\beta = 0$ %), the increase in the mean runoff under the influence of the forest and the general zonal factors amounts to 15-70 %.

Owing to the observed latitudinal-zone character of annual runoff, good relationships are also obtained, as a rule, between runoff and latitude (Fig. 2, d), for such cases when the forest cover of watersheds also has

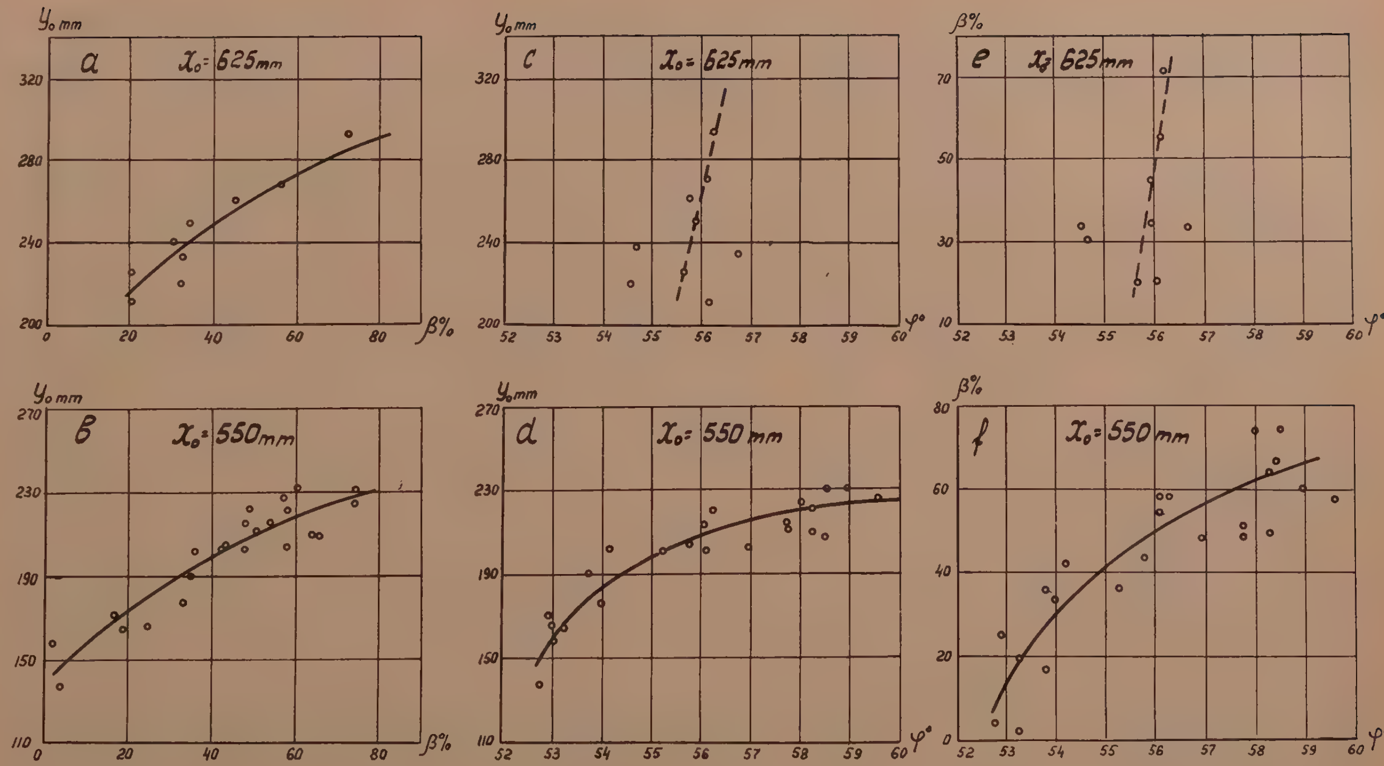

Fig. 2 Relationships between mean annual runoff (y_0 mm), latitude of watershed centres (φ°) and forest cover (β %), with mean annual precipitation (x_0) of 625 mm and 550 mm.

latitudinal-zone character (Fig. 2, f). If, through any natural causes, the forest cover of the river-basins under consideration proves smaller or greater than the average for that particular physico-geographical region (Fig. 2, e), a marked departure from relationship between latitude and runoff value is generally observed (Fig. 2, c). In such cases watersheds with forest cover greater or smaller than the average for that particular area usually have a heavier or, respectively, lower mean annual runoff than the average river runoff for the area.

This justifies a conclusion that, apart from general physico-geographical factors, the forest plays an important role in river-runoff formation and generally contributes to an increase in the runoff of rivers.

The presence of forest on watersheds (of 1000 sq.km. and over in area) usually promotes stable subsurface feeding of rivers which with favourable hydrogeological conditions may increase from two to four times under the influence of the forest. On forested watersheds, floods and high water usually smooth over, their duration increases, while peak discharges are, as a rule, somewhat lower.

It should be noted that on medium and large rivers whose watersheds have a considerable forest cover, over 30 % of the water absorbed by forest soils reaches the river-bed through subsurface flow and is discharged in flood- and high-water periods.

Subject to hydrogeological conditions, relief, the type of soils, carst phenomena, marshiness, presence of lakes and other factors, considerable deviations from the above relationships may be observed.

Records for over 40 river basins were used in analysing values close to annual evaporation from watersheds (x-y), determined by subtracting runoff (y) from precipitation (x), for water-years (October-September). The basins were divided into groups, each (2 to 6 watersheds) comprising basins in the same physico-geographical region which are similar in watershed area but distinctly different in forest cover. The analysis indicated a very satisfactory relationship between the annual values (x-y) and x for each group of watersheds. Several specimens of such relationships are given in Fig. 3. The relationships obtained reveal that the value (x-y) characterizing total evaporation (accumulation included) for most river basins, with annual precipitation of as much as 400-500 mm, irrespective of the extent of the watershed's forest cover, is in linear relationship with total annual precipitation (x); with precipitation of over 400-500 mm there is a trend towards smaller total evaporation value (x-y) as the extent of the river basins' forest cover progresses.

For each 10 per cent increase in watershed forest cover the total evaporation (x-y) decreases on the average by 5, 3 and 2 per cent with the precipitation for a given year of 600 mm, 500 mm and 400 mm, respectively.

The decrease in total evaporation in the forest as compared with open areas in the years of heavier rainfall is quite explicable from the physical point of view.

Taking into consideration that runoff in wet years as well as in years of high and above average water-supply (20 to 50 per cent of the total number of years) accounts for as much as 40 to 70 per cent of the mean long-term river runoff formation in the U.S.S.R. in Europe, it becomes quite understandable that in individual years, even with considerable differences in the extent of watersheds'forest cover, it is often impossible to find noticeable differences in annual runoff values.

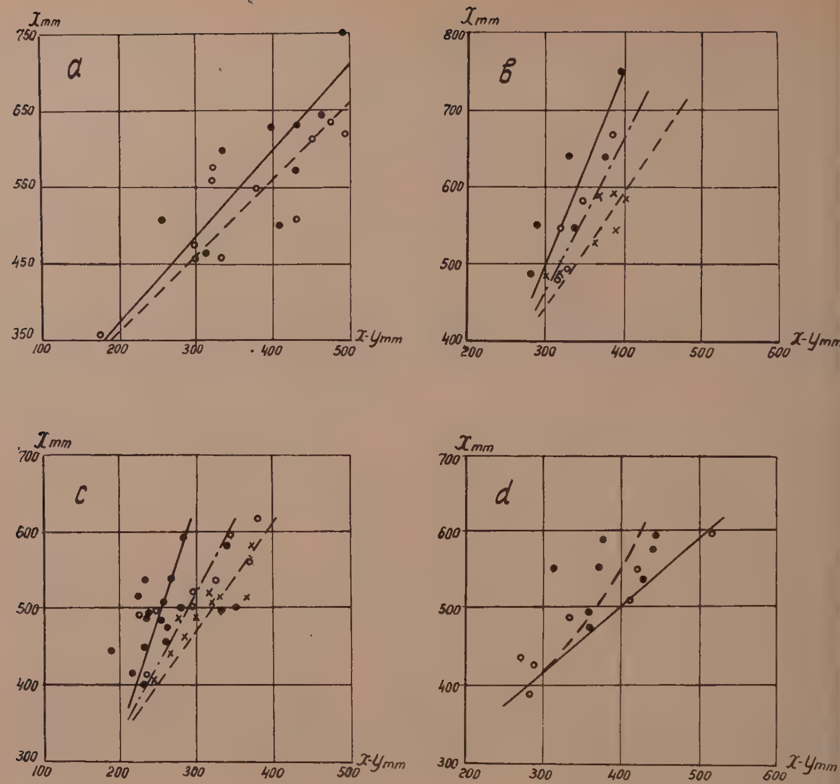

Fig. 3 Relationships between annual precipitation (X) and the difference of precipitation minus runoff (X-Y) mm

(a) ● Pliussa River, watershed area F = 5090 sq.km.; forest cover β = 60 %;

○ Luga River, F = 6320 sq.km.; β = 46 %;

(b) ● Velesa River, F = 1400 sq.km.; β = 72 %;

○ Obsha River, F = 1530 sq.km.; β = 54 %;

× Svolna River, F = 1430 sq.km.; β = 39 %;

(c) ● { Kobra River, F = 7200 sq.km.; β = 96 %;
Moloma River, F = 6250 sq.km.; β = 88 %;

○ Cheptza River, F = 5480 sq.km.; β = 54 %;

× Bystritza River, F = 3540 sq.km.; β = 15 %;

(d) ● Ugra River, F = 15 300 sq.km.; β = 25 %;

○ Oka River, F = 17 500 sq.km.; β = 4 %.

In the light of the above, an explanation suggests itself of the discovered increase in mean long-term annual runoff in connection with greater watershed forest cover. Calculations based on the foregoing data concerning variations of the value (x-y) and general conditions of mean long-term runoff formation indicate that for a forested river basin ($\beta = 100\,^0/_0$) a mean long-term annual runoff should be 20 to 60 per cent greater than that from a similar open (unforested) river basin. The results of such calculations are in complete agreement with the conclusions stated above.

It should be noted in conclusion that runoff formation on small watersheds and on river basins differ considerably due to the difference in conditions and share of the subsurface flow. Therefore, the effect of their forest cover may lead to opposite results — decreasing runoff on small watersheds and increasing it on medium and large rivers.

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THE INFLUENCE OF FORESTS ON GROUND WATER LEVEL

by V. V. RAKHMANOV

SUMMARY

Investigating the ground water levels in forest plantings and woodless land at the end of the past century Otozky found that in the late summer and in autumn they are in the most of cases lower in the forest than in the field. According to him this is due to the great forest transpiration.

Although the results of some subsequent investigations don't coincide with the above mentioned data the latter were used to explain the drying up effect of forests recognized by many specialists even at the present.

The study of the initial data in former investigations of the effect of forests on the ground water level and the material of the present hydrogeological observations carried out by us made it possible to find out the following features.

1. The relationship of the ground water levels in the forest and field revealed by Otozky usually remains during the whole year, including the winter season when the consumption of water for transpiration is not observed. Consequently the lower position of the ground water level in the forest compared with the field doesn't result from the greater consumption of water for transpiration of forest vegetation.

2. The ground water regression in the forest and field is observed during the whole year, in winter the difference in ground water levels in the forest and field does not decrease and in some cases it is even increased. There is no any depressions observed under the forest plantings that appear as a result of great evaporation in summer and fill because of water inflow from woodless area in winter.

3. In the attempt to reveal the effect of forests on ground water Otozky studied the latter at rest. The changes of ground water levels were explained by ground water increment as a result of precipitation and by the consumption of the ground water for evaporation and transpiration. Actually the ground waters are as a rule in the state of motion and their levels decrease as a result of outflow and the depletion of ground water resources.

4. The properties of wood soils and ground are the best ones for infiltration and this phenomena is confirmed by the special investigations and routine practice of many people. It happens because of the fact that forests are often situated, especially in the forest-steppe and steppe, on the more coarse sand soils which are less suitable for agriculture and because of the crumbling effect of the tree roots and a number of animals named shrews.

According to the laws of ground water motion the increase in permeability (filtration coefficients) of soils and ground results in ground water regression. As the wood soils and ground are more permeable the levels of ground waters when they move from field to forest must inevitably decrease.

5. There is another reason of ground water regression in forests. The most of studied forests grow on the soils that are not suitable for agriculture namely on the strongly eroded zones near the slopes of river valleys, gorges and gullies. The lowering of the moving ground water table occurs in the form of curved depression in the direction of the river valleys, gorges and gullies, the ground water levels under them are lower than in the fields situated at the watersheds.

6. However, the hydrogeological conditions are not always favourable for ground water regression in the forests. At the plains where the ground water motion doesn't practically exist or it is very small the levels in the forest and field are almost even. The variation amplitude of the latter because of rains and evaporation (transpiration) in the forest doesn't much differ at these conditions from the amplitude in the field.

The similar picture is observed also in the less flat country with ground water flow being in the coarse-grained permeable soils, for example, in the sand alluvial river valleys. In this case the crumbling effect of forest can't much increase the great permeability of soils. That's why when the ground water moves from the woodless land to the forest area the filtration coeffi-

cient here doesn't essentially change; according to the Dupuit and Darcy's formula ground water levels don't change neither.

Thus the main cause of the lower position of the ground water levels often observed under the forest lies in the features of the hydrogeological conditions of a locality which partly arise due of the influence of the forests.

Résumé

Après certains rappels historiques, l'auteur présente les résultats de ses recherches :

Le niveau des nappes est plus déprimé sous les forêts que sous les champs, non seulement en été, mais aussi durant la saison froide. Le rabattement sous les forêts par rapport à ce qui se passe sous les champs ne peut par conséquent être attribué à la transpiration plus marquée de la forêt.

L'auteur estime que le plus profond rabattement de la nappe sous les forêts dépend, d'une part, du fait qu'elles se trouvent généralement au bord des profondes coupures de terrains occupées par les cours d'eau et, d'autre part, par le fait qu'elles occupent en général des aires sablonneuses, moins fertiles, mais plus perméables et qui le sont rendues plus encore par les galeries qu'y creusent les animaux : cette plus grande perméabilité conduit d'après la loi Darcy à une plus faible pente de la nappe et par conséquent à un rabattement plus marqué.

Les conditions hydrogéologiques ne sont cependant pas toujours favorables à ce rabattement plus prononcé en forêt : c'est notamment le cas dans les plaines où l'écoulement de la nappe est très faible et aussi dans les sols très perméables (par exemple des nappes alluviales) quand la grande perméabilité du sol ne peut guère être augmentée sous la forêt par l'activité des animaux.

The problem of the afforestation influencing on the ground water level and soil moisture is long ago of interest to scientists studying the water conservation effect of forests. It was considered for a long time that the forests provide favourable conditions for the increasing of the amount of precipitation, moisture storage in soils and of water source feeding. This point of view widespread at different countries was dominant in the scientific literature till the end of the past century.

However, even in the middle of the past century facts were known which seemed to show the drying up effect of the forest.

In nineties of the past century P. V. Otozky (14) made a number of synchronous ("parallel") observations of the ground water level in forests and the neighbouring woodless lands ("in the field") at some localities of the European part of the USSR, from the forests of the North-west (the Estonian S.S.R. and the Leningrad region) to Shipov and Semenov forests in the Voronesh region and the Cherniy Les in the Kirovogradsky region.

Investigations by G. N. Visozky in those made by P. V. Otozky and later on the works by P. K. Falkovsky and other autors about the moisture content in wood soils resulted in the point of view on the forest as a great moisture waster which lowers ground water level and soil moisture content.

Observations made by P. V. Otozky in summer and autumn months during his "excursions" to the forests of different types and different soil-climatic conditions showed that almost everywhere ground water levels in forests are lower than in zones of neighbouring woodless lands. This fact was considered as undisputable evidence of the great transpiration of moisture by trees and other forest vegetation, ground water depletion drying up of the land.

Even after the publication of the first results of the investigations obtained by Otozky, which gave rise to the quick response in scientific

circles, the regular observations of the ground water levels in forests and fields of different countries were started.

The great part of the observations confirmed the Otozky's conclusions on the ground water lowering by forests; however; some of these observations, namely Nikitin's (13), Tolskiy's (19), Ebermayer's and Gartman's observations did not reveal this phenomenon. The observational results of the subsequent period are also far from being in agreement with each other.

However, in almost all cases when the ground water levels were in forests lower than in open lands we can observe this phenomenon not only in summer when it can be explained by great water losses by transpiration, but also in winter when there is no transpiration at all.

In accordance with the investigation of U. F. Gotshalk in this country (8), Pirson—in India, Buchler—in Switzerland, Kokkonen—in Finland (24), ground water levels in forests are lower than those in fields. But according to the observations by E. S. Vasiljev (4, 5) and A. A. Molchanow (11) the correlation between ground water levels in forests and fields is different: sometimes the levels are lower in the forest, and sometimes vice versa.

As an example a schedule of ground water level fluctuations in the forest and in the field, made up on the basis of Henry's observational data is given (Fig. 1)

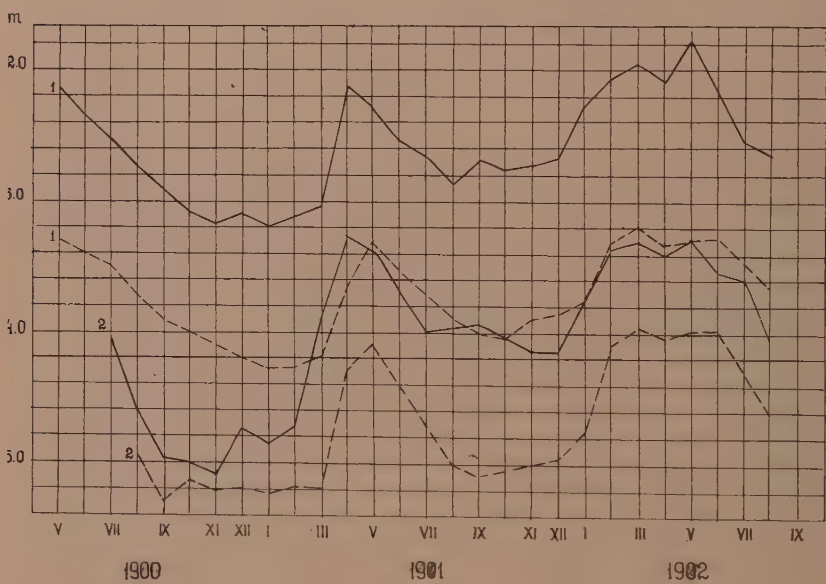

Fig. 1 Variation of the ground water levels in the field and in the forest of Mondon (France). 1 and 2-the first and the second wells.
1 ———— in the field, — — — — — in the forest.

It is obvious that if ground water levels all over the year are found in forests lower, than in fields this phenomenon cannot be explained by great transpiration of forest, and the very fact of lower ground water standing in the forest cannot be used as an evidence of the different values of the transpiration.

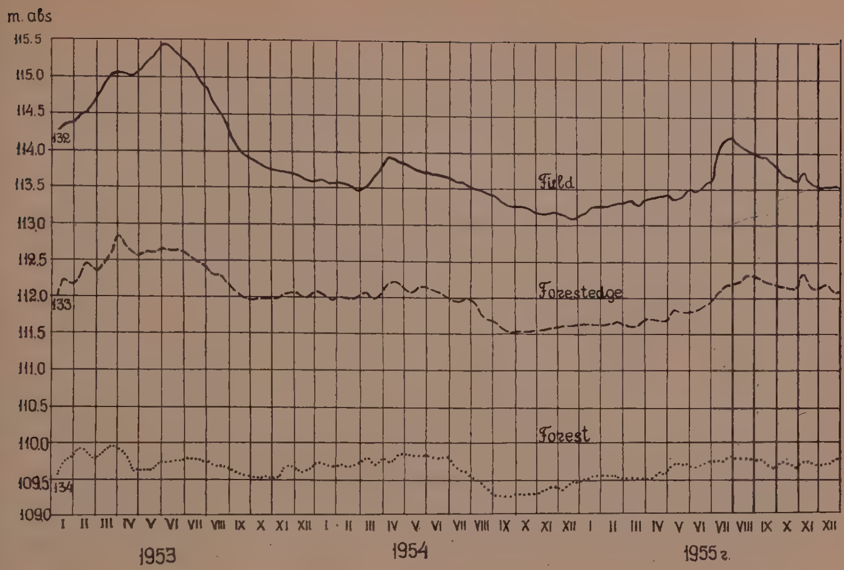

Fig. 2 Variation of the ground water levels in the field and in the forest near the Zyganskaja village of the Voznesensky district, Nikolaevskaja region in 1953-55.
——————— well No. 132 (field), — — — — — well No. 133 (wood edge), ... well No. 132 (forest).

With a view to define our presentations of forest influence on ground water levels more accurately and find out the reasons of their lowering, we considered the parallel observations of the ground water levels in forests and in fields, made during the last years in different points of the USSR. Fig. 2 shows the modification of ground water levels during 1953-55 in the deciduous wood and in the field near the Ziganskaja village, in Voznesensky district, Nikolaevsky region. Observation wells are laid in weakwaved country within 14-15 km from the South Boog river far from a broad flat gulch.

A powerful alluvial ground lies under a soil layer in the wood and field area.

As we can see ground water levels at the wood edge are lower than the levels at the wood edge and this correlation all over the year, including the winter period.

We come across the same phenomenon in the other points of hydrological observations for instance the Cherniy Les (the Ukraine) where Otozky made his observations in former times, in Kamennaja Step (the Voronesh region), in the territory of the Bolshaja Saraevskaja flow station near Moscow and also in Valdayskaja research hydrological laboratory near the town of Valday. We may consider that the lower of ground water levels in forests as compared with these in fields are an usual thing in different soil-climatic areas. However, on the basis of this phenomenon we can't draw a conclusion of the great forest transpiration capacity.

If the latter were the main reason of lower ground water levels in forests they would be lower there than in fields only at the end of summer or in

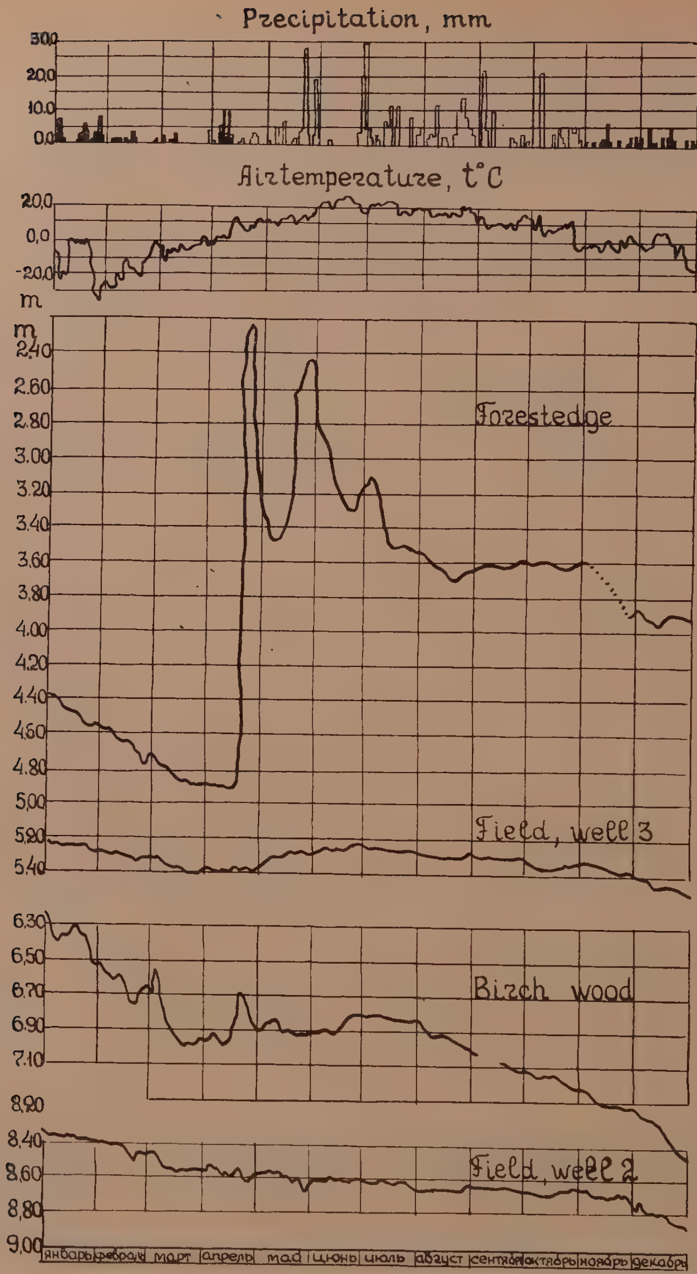

Fig. 3 Variation of precipitation, air temperature and ground water levels in the field and forest of the Medvenka river basin (tributary of the Moscow river), 1956.

autumn due to the large water losses by transpiration during the vegetal period.

But in winter when the transpiration ceases the difference between the levels in forest and fields would disappear little by little or at least it would considerably decrease under the influence of ground water inflow to the forest from the surrounding lands.

Really, in those points where the lower ground water bedding is found under the forest it usually remains there all over the year, including winter, when the water loss by transpiration ceases. Moreover, the ground water regression in forests found in summer which seems to be the result of water loss by transpiration, also continues in winter and it is often much more intensive than in summer if during the thaws inflow of snow melt from above does not occur. This fact is well confirmed by the regular hydrological observational data obtained in forests of different localities especially in the areas of stable winter where ground water levels are the lowest at the end of winter. (Fig. 3). According to the mean observational data obtained in different forest-plantings of the Lesnaja Dacha of the Timirjasev Agricultural Academy of science in Moscow (21) for several years the greatest ground water regression occurs everywhere in March and April (Table 2). Noting above-mentioned statements it becomes obvious, that lower ground water levels in forests as compared with woodless country, found in summer and winter can't be explained by the transpiration influence of wood vegetation which occurs only in summer: they are the result of some other constant factor acting all over the year.

TABLE 2

Average monthly values of ground water levels in the Lesnaja Dacha of the Timirjasev Agricultural Academy for the period of 1906-39

No. of districts	00	0	1	2	3	4	5	6	Severnaja Jama.
January	1,52	5,03	3,20	3,52	6,35	6,18	6,17	5,93	0,73
February	1,57	5,05	3,22	3,57	6,39	6,20	6,32	5,88	0,36
March	1,59	5,08	3,26	3,61	6,44	6,23	6,29	6,03	0,87
April	1,38	5,02	2,88	3,38	6,44	6,23	6,20	5,99	0,36
May	1,17	4,93	2,56	3,16	6,28	6,13	5,93	5,77	0,37
June	1,25	4,92	2,88	3,25	6,19	6,07	5,88	5,72	0,58
July	1,32	4,90	2,99	3,93	6,14	6,08	5,89	5,71	0,68
August	1,37	4,92	3,02	3,36	5,15	6,07	5,94	5,74	0,74
September	1,39	4,99	3,09	3,41	6,19	6,08	6,00	5,78	0,74
October	1,44	5,01	3,11	3,44	6,29	6,10	6,06	5,83	0,67
November	1,47	5,02	3,10	3,44	6,30	6,14	6,09	5,87	0,58
December	1,49	5,02	3,16	3,48	6,32	6,15	6,11	5,90	0,61

This factor is to be looked for in the particular hydrogeological conditions under forest plantings causing a specific ground water regime in them which differs from the woodless area regime.

It should be taken into consideration that the correlation of ground water levels in the forest and in the field found in nature occurs not only as a result of ground water increment and its loss by evaporation but also to a considerable extent as a result of ground water movement, its inflow and outflow.

Ground water outflow in the direction of slope causes the constant depletion which is first of all displayed in the ground water regression in the forest and in the field found in periods when there is no large ground water increment. In this case the rate of ground water depletion is determined by the rate of the outflow exceeding the bounds of a given place and finally entering the sources and rivers.

It is known that the ground water discharge at any section depends on the filtration capacity of the ground, the depth of the flow, and the slope of its surface. Its general form is represented by Dupuit's or Darcy's formulae. The latter can be written as following: $q = khI$ (for the unit of flow width), where q-is the discharge of ground water flow for the depth unit in m^3/sec, k-filtration coefficient in m/sec, h-the mean flow depth in m, I-the slope of the ground water surface.

According to this formula at the same discharge the flow, its depth and consequently the ground water levels vary with the changing of slopes and filtration coefficients.

First let us assume that the movement of ground water occurs in homogeneous soils in the direction from the divide basin to the river valley or to some other natural depression of the ground where the ground water decrement takes place.

In this case the surface of ground water flow takes the form of a curved depression, its fall (slope Y) increases approaching the river valley and that's why the ground water level decreases.

If the forest grows near the river valley (gorge or gulch) then the ground water levels under them must be inevitably lower than under neighbouring fields or other woodless lands which are (situated) farther from the river.

It is obvious that in this or other similar cases the main reason of ground water regression under the forest does not consist in the great water transpiration by wood vegetation but depends on the hydrogeological conditions of the locality causing the fall of ground water table.

Really forests are often situated near river banks gulches or gorges. And it is quite clear because the areas less crossed by gulches on slopes and divides are long ago used for agriculture. Almost all large forests investigated by Otozky are situated nearer to river banks and other natural cuttings of the ground than woodless areas where synchronous observations of ground water were made. That's why it is natural that in the most observational points of this author the ground water levels in forest are found to be lower than those of woodless areas. The same can be said about forest plantings investigated by G. N. Visozky and many other authors. Such is one of the principal reasons of ground water regression often found in forests but not the only one.

Lower ground water levels in forest plantings can form under more or less equal disposition of forests and fields with regard to hydrographical network if wood soils and grounds have a great permeability that is the great filtration coefficients.

It follows from the same Darcy's formula. For an adequate water discharge under the same slope of ground flow table smaller depths are observed and therefore lower water levels if the filtration coefficients increase. The increase of the permeability of the ground results in lowering of ground water levels other conditions being equal. Wood grounds are well known to be of the great permeability as compared with grounds of some different kind.

The author considers that one of the explanations of this phenomenon consists in the fact that forests often grow on large-grained usually sandy grounds and soils which filtrate water better than small-grained field and meadow grounds especially in the forest-steppe and steppe regions. This regularity still observed by E. E. Baer (22) is formed both by natural conditions of interaction between forest and steppe and by development of agriculture which requires more suitable lands for crops.

However, crumbling effect of the forest vegetation and shrews also influence wood soils and the latter acquire the great permeability. In order to define the crumbling effect of the forest special terms "root drainage" and "biodrainage" appeared in literature. Particularly the efficiency of such a drainage is verified in artificial wood plantings.

Being planted on field soils or other woodless soils they considerably increase their permeability in the process of growing.

So according to the data obtained by V. P. Suharev and E. M. Suhareva (2) the rate of absorption under 60 years old forest zone is 1.5—2.0 times greater than in fields or pasture lands. According to observations made in the U. S. the infiltration efficiency in the zone of 20—40 years old white acacia plantings is almost twice as great as in the zone of the young up to 10 years old white acacia plantings (10).

Under forest-plantings the coefficients of horizontal filtration essentially increase. In the Kamennaja Step forests zones they are 1.5—2.0 times greater than in the neighbouring fields. The filtration coefficients defined in forests of the Medvenka river basin (near Moscow) are usually 3—5 times greater than in fields.

The ground water levels observed at the 5—6 m depth under the forest zone rise quickly in spring as soon as the snow melting begins (Fig. 3) and then we can observe a quick regression while in the field their rise and regression occur very slowly. We can see the rapid infiltration in snow melt ground in forest zones from the strong fall of ground water temperature at the beginning of snow melt.

If there are waterproof loamy layers in the ground under the forest the powerful tree roots are going through "make holes" in them thus creating conditions for speeded up movement of moisture from the top to bottom in the direction of pervious ground layers. Due to this fact water from precipitation quickly reaches the deep layers and often rises the ground water level without wetting the whole thickness of the ground (5,9).

Excavations of grounds made by us near the town of Uruepinsk the Stalingradskaja region and near the settlement of Firsanovka, the Moskovskaja region, after rains and special waterings confirmed this phenomenon very well (Fig. 4).

If a large amount of roots developing and dying off during the long wood planting life is taken into consideration it may be assumed that the root drainage of the latters considerably exceeds by its efficiency the artificial drainage with the help of stakes which is used for a long time for the drainage of low lands in Holland and other countries.

Fig. 4 Water percolation in the wood soil near the town of Urupinsk, the Stalingradskaja region, after the heavy rain in August 1952.

It should be noted that the tree roots may penetrate to a very great depth especially in the south where the ground waters are very low. There roots depth of 5—6 m is a usual phenomenon. When digging Suez Canal they came across roots of tamarind which were 30 m long (15).

We think also that this crumbling effect of trees should not be underestimated at least in the upper ground layers which is the result of a constant swing of trees lasting day by day due to the wind. If trees are often pulled up by the roots under the influence of strong winds there is no reason to deny the possibility of crumbling the wood soils by the swing.

The relatively great permeability of wood soils in winter is due to their smaller freezing because of the above protection of soil covering.

There is no doubt that all these factors contribute to the maintenance of the great amount of wood soils and grounds in relatively crumby state with the great pervious capacity. The increase of filtration coefficients in wood grounds inevitably results in decrease of ground flow depth and con-

sequently of ground water levels under forests. From the author's point of view this is the second not less important reason of ground water levels decrease in forests as compared with woodless lands.

It should be noted that due to the great permeability of wood soils when there is an active snow melting in spring and after rains in summer it may be also observed in forests in comparison with fields up to higher levels. But because of the rapid water outflow they fall quicker than in fields (Fig. 3).

However it should be noted that this reason does not show its influence in a number of cases because the crumbling effect of wood plantings proves to be ineffective. For example let us take wood and woodless lands which have sandy of road-metal grounds as an underlaying surface with a good permeability and a great filtration coefficient. In this case even the strongly developed root habit of trees does not much increase the great permeability of such grounds. As the filtration coefficients remain more or less constant when passing from fields to forests the somewhat considerable lowering of ground water level in forests as compared with fields doesn't occur. Such were the conditions in which Ebermayer and Hartman (25), A. A. Molchanov (11) and some other authors made their observations and the fall of ground water levels in forests growing on sandy soils was not registered. G. F. Morozov (12) and Visozky (7) came across the same phenomenon and the sandy soils were called "feeders" of rivers.

Probably the small filtration coefficients' change of grounds as passing from fields to forests may occur when wood plantation is not enough developed and has no powerful root habit required for soil crumbling different depths. Of course at the conditions when ground flow passes from fields to forests the water levels don't considerably change.

Explaining the ground water level lowering in the forest mainly by hydrogeological conditions and not by the great transpiration of wood plants we may solve some other important contradiction which arises when the hydrological role of forests is investigated. According to the investigations by Sokolovsky and many other authors (2, 3, 16, 17) made in the flat country of the European part of the USSR the average annual river flow increases with the extension of wooded area basin. At the same time the flow gauging from small watersheds in the US (23, 28, 29) and in other countries (27, 30) show that its annual value in wood watersheds are smaller than in woodless ones.

This contradiction which cannot be explained from the point of view of the transpiration theory is easily understandable in the light of hydrogeological conception. Indeed, if in forests the ground flow levels are lower than in woodless areas then the ground water decrement in them can take place only in deeper depressions of the ground and within the large basins. But in small watersheds ground water decrement should occur more seldom and ground water feeds the surface streams less than in woodless watersheds. However the ground water levels are lower with evidently smaller losses by evaporation some time or other they appear on the surface feeding the water streams from the greater watershed area. Therefore the role of ground water in the feeding of rivers which have great wooded basins increases. It is the above mentioned phenomenon that explains the fact that the flow from small wood watersheds seems usually smaller than the flow from small woodless watersheds and at the increase of watershed area the opposite phenomenon is observed: with the increase of wooded areas the flow increases.

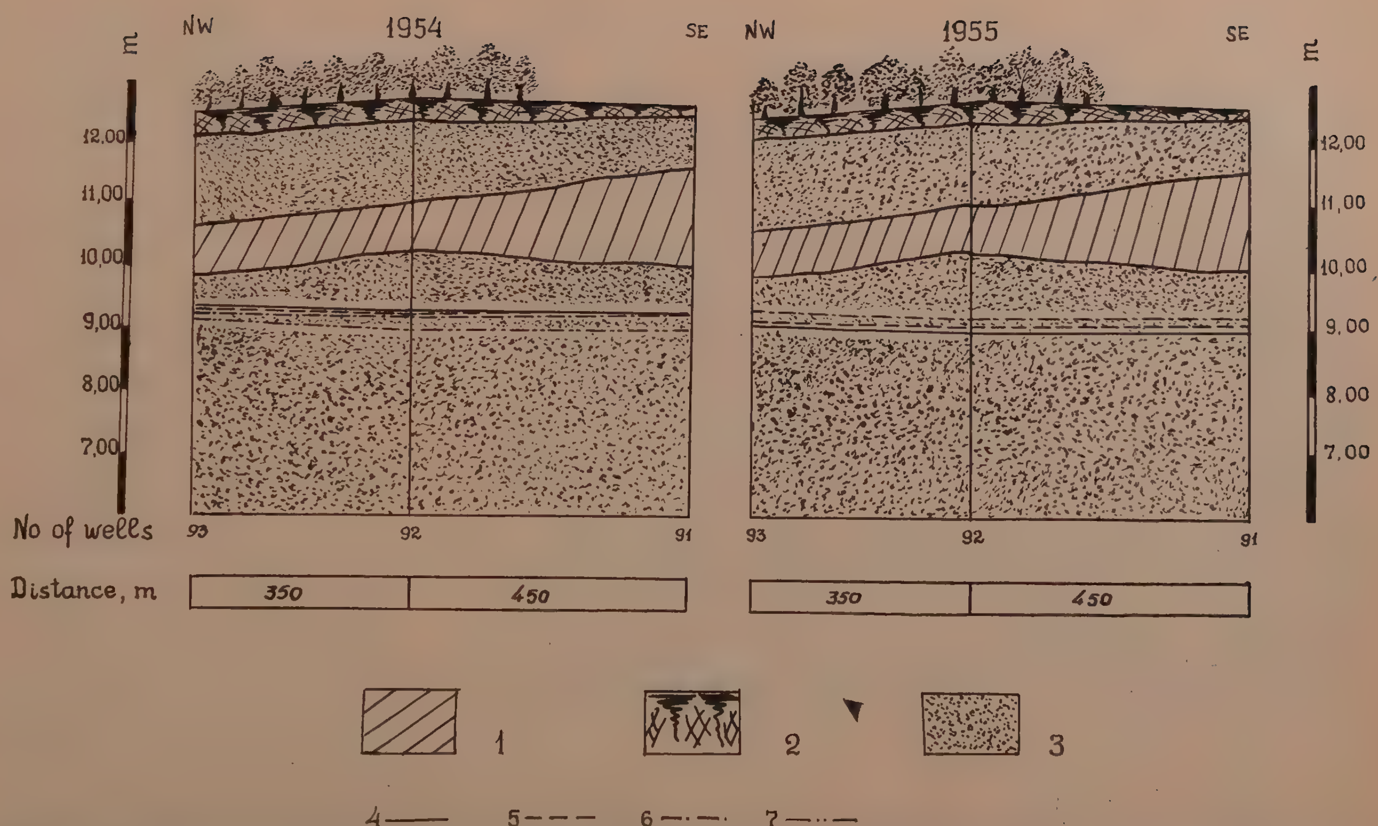

Fig. 5 Variation of the ground water levels in the forest and field near the village of Radenskoye of the Zurupinsky district,

We think that the great stability of wood water sources is explained by deeper ground water bedding in the forest and their decrement in deeper depressions of ground which are draining the greater watershed area. Thus, according to Fishbah's investigations (26) the correlation between maximum and minimum water source debit of woodless lands in Switzerland is equal to 10 but in wood lands it does not exceed 1.5. But deeper ground water bedding in forests being a widespread phenomenon occurs however not everywhere. In flat badly drained lands the ground water table is almost at the same level in the forest and the field.

In Fig. 5 the hydrogeological profiles are presented for 1954—55 in deciduous plantations and in the field which is situated on the very flat second terrace of the Dnieper river. (The Hersonskaja region). Here the small-grained sand is under the soil up to the depth of 1.5—2.0 m and under it there is a layer of loamy soils of about the same thickness. Lower the small-grained sands of an ancient alluvial origin are extending to the great depth and the pearched pressureless ground water horizon is revealed in them.

In spite of the great permeability of soils due to the lack of somewhat appreciable slopes the ground water movement is very small here. That's why in such conditions the difference between ground water levels in forests and fields is not observed. As it is seen at the diagram the ground water levels for two years (and from additional data available for the next years also) were almost the same in the forest and field and even sometimes the small fall of levels was observed in the direction from the field to the forest.

Almost the same levels in the forest and in the field are also found in Danube river flat country, Odesskaja region territory.

In both points the ground water bedding is not deep 1.0—1.5 m from the surface that is within the reach of the plant roots. In spite of this the lowering of the ground water levels in the forest as compared to the field is not observed as it should be expected if the transpiration of wood plants had had a strong influence on their levels. The ground water level in different seasons changes more or less equally both in the wood and field areas.

Almost the same ground water levels in forests and fields were found all over the year in the flat countries from observations made by a number of other authors, namely by I. S. Vasiljev (4) on the Mologo-Sheksninskaja flat country by A. P. Tolsky (19) in the flat dampy land near the town of Staraja Russa et cetera.

This phenomenon can't be understood from the point of view of the transpiration theory explaining the lowering of ground water level by water consumption of plants. If due to this great transpiration the forest has an ability of the intensive ground water consumption then the ground water regression under the forest as well as the subsequent rise of ground water level in winter would be especially observed in the flat country with the more or less plane ground water table. Indeed it is in the flat country that the ground water regression doesn't exist. If the levels change from season to season their change is more or less adequate in forests and in fields.

However, noting the fact that ground water levels first of all depend on the movement conditions of the water the fact of their small difference in forests and in fields of the flat country is quite understandable. Due to the absence of slopes the ground water flow does not arise or the ground flow rates are extremely small. Therefore even the great difference in filtration coefficients of field and wood soils can't much influence the depth of ground flow and consequently the ground water levels. In these conditions their

table is more or less horizontal; this phenomenon is usually observed in water basins without any flow. In this case the ground water level fluctuation is explained by ground water increment and water loss by global evaporation. The equal fall of levels during the summer shows the same water loss by evaporation and transpiration of wood and field areas.

We shall consider another phenomenon which is often remembered when investigations of the wood influence on the ground water are made. We mean the swamping of the cleared space which begins as a result of the ground water level rise after the wood cutting.

The facts of swamping often are given to prove the drying capacity of the forest. Pointing out the strong decrease of evaporation after the cutting down they usually forget the fact that in the place of cleared space any other vegetation does not exist and for a number of years the ground surface remains well protected from the evaporation by the slowly decaying dead cover from soil covering and woody waste products remaining after cutting.

The computation shows that in damp areas where the ground water bedding is not deep and its outflow is very slow the small decrease of the water loss by evaporation, to tens of millimetres only, is enough for the ground water levels rise during some years to a great extent sometimes up to the ground water decrement and thus causing the overmoistening and then the swamping of soil too.

The forest removal in such places influences the decrease of total (global) evaporation so far as the forest is a user of water. This fact may cause both the ground water rise and the swamping of soils in the place where the ground water outflow is very slow. However it does not mean that the forest is a great water absorber which has a larger ground water discharge than any other plants. The soil swamping under conditions of their bad drainage may also occur when the plants of other types are removed for example as a result of fires. The phenomena of the wood swamping of different type and age are also well known. This fact contradicts with the idea of the wood draining influence in general.

On the contrary under conditions of a good ground water outflow (when the land is crossed and the soils are pervious) after felling even in the north areas to say nothing of more arid zones in the South, the swamping of cleared spaces is not observed.

In the case of quick covering by thick grassy plants the cleared spaces do not swamp and even G. H. Visozky (7) such a great supporter of the drying up effect of the forest on flat lands supports this point of view. It confirms once more that the absorbing capacity of the grassy vegetation is not smaller than of the wood.

Therefore, observed under certain conditions the swamping of the cleared spaces shows only the fact of water consumption by wood vegetation but can't prove the fact that global water flow from wood lands considerably increases such a flow from other lots.

So the investigation of the ground water level correlation in forests and fields (noting their movement in different hydrogeological conditions) permits to give up the opinion of the great absorbing capacity of the forest and to explain the above mentioned phenomenon in order to prove the drying up effect of the forest and to get rid of many contradictions which inevitably arise in using the transpiration theory.

From the point of view of the author it may be assumed that in most cases forest providing favourable conditions for the ground water outflow

cause their decrease by evaporation and transpiration and therefore the increase of rivers and water sources feeding. Such assumption is confirmed by the data of the annual flow increase with the increase of wooded basins in the USSR.

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FORESTS AND WATER

by A. A. MOLCHANOV

(Thesis of report)

1. The interaction between forests and water is very complicated. Water consumption by forests changes from zone to zone. Within any definite zone the water consumption changes in various types of forests, in stands of various composition, age and density. The water discharge on a watershed depends also on the percentage forest coverage and the distribution of forest over it.

2. The amount of water arriving at the surface of the soil on a watershed is closely related to the composition of tree species and within a single tree species it depends on the age of the stands and the density of their crowns. Precipitations are retained maximally by the crowns of silver fir stands these being followed in decreasing order by fir, beach, pine, oak, birch, aspen and ash stands.

3. The amount of precipitations arriving at the soil is also closely connected with the surface runoff on the watershed, which within any given geographical zone changes with country relief, geological structure, mechanical composition of the soil, development of the bedding on the soil surface and depending on the activities of man as well as on the densification of the soil and the injury to the bedding caused by cattle.

4. In watersheds with highly permeable sandy soils the surface runoff is a minimum and, if they are underlain by water-resistant geological strata, all the water seeping into the soil wedges out into the river network of a single watershed; on heavy loamy and clayey soils with well-defined soil structure and developed bedding all the water also seeps into the soil on slopes even up to 25° and passes into the rivers by soil runoff. If the soil is superficially densified well-defined surface runoff is observed even on slopes down to 5°.

5. Besides the amount of precipitations falling on the watersheds and the water capacity and permeability of the soil, the inflow of precipitations into rivers depends on the total evaporation value, which is dependent not only on the amount of precipitations on the watershed and of the meteorological conditions, but of the composition of the forests as well. The maximum total evaporation is observed for larch stands followed in decreasing order by fir, pine, oak, aspen, ash and birch stands.

6. Within the same species the total evaporation varies with the age of the stands. The highest total evaporation is observed in the accretion culmination period. Within a zone of mixed wide-leaf forests and forest steppes, culmination of accretion is observed in fir stands at 60 years of age, in pine—40, in oak—50 to 60, in aspen, ash and birch at 30 years of age.

7. Within the same age the total evaporation in a zone of mixed wide-leaf forests varies with the density of stands. The highest evaporation is observed in densities of 0.4 to 0.5, then in 0.9 to 1.0 and the least evaporation is in densities of 0.7 to 0.8. In the steppe zone the lowest total evaporation is observed at densities of 0.5 to 0.6 and in taiga zones at 0.8 to 0.9.

8. The total evaporation from fields does not remain constant either, but varies depending on their size on the watershed. Besides, it changes depending on the types of cultures and on the agrotechnical methods employed.

9. On large fields the water conditions of the soil are influenced, aside from evaporation, by the blow-off of snow by the wind. The highest loss of water due to total evaporation and to snow transportation by the wind is observed on medium size fields. Then it decreases on approaching the forest wall. The lowest evaporation is observed on fields from 0.25 to 1 ha.

10. In connection with the above the water consumption in a forest may be either greater or smaller than in a field. In the accretion culmination period the forest consumes more moisture as a rule than the field, while young trees up to twenty years of age and mature of 90- to 100-year-old pines and oaks consume less water than fields. Ash, aspen and birch trees 90 to 100 years of age consume less water than fields. Overaged and distinctly tired mature stands of firs and even leaf-bearing species consume more moisture than fields.

11. With artificially improved mineral nutrition vegetation both in the forest and in the field consumes comparatively less water than if the soil is not fertilized. Both forest and agricultural vegetation is more drought resistant on fertilized soils.

12. With natural soil fertility not changed by man the water consumption is smallest on dry sandy soils; as the soil becomes moister and more fertile the loss of water due to total evaporation increases; waterlogged soils covered with pine, fir and leaf-bearing stands lose a great deal of water by total evaporation and greatly limit the amount of water available for runoff.

13. Depending on these factors the water drainage to rivers also changes. If the watershed combines forest areas consuming little water and fields consuming a lot of it, the water runoff to the forest rivers is greater than to field rivers, the precipitations being equal. With other combinations of tree species and ages of stands the forest areas may consume more moisture than the field areas, and the runoff from forest rivers will be lower.

14. The highest river runoff is observed at 30 to 40 per cent forest coverage woodiness with the watershed situated uniformly on slopes and ensuring interception of all surface waters and their transference to the soil runoff.

ON THE EFFECT OF THE FOREST ON THE REGIME OF THE RIVER FLOW

by Prof. D. L. SOKOLOVSKY

SUMMARY

I. The question of the effect of the forest on the regime of the river flow is one of the most disputable problems in the hydrology and science of forest. The reasons are the complexity and variety of the factors involved, affecting the elements of the water balance of the forest and field watersheds, as well as the uncomplete and inaccurate account of some of them in the experimental investigations of this question, in particular the amount of the infiltration of the snowmelt and rainfall waters and contribution of them to the ground water, the amount of the transpiration and evaporation from the vegetable cover.

As a result, the incomplete and inaccurate equation of the water balance has been solved artificially and used as a base for the quite opposite opinions of the effect of the forest on the regime of the river flow. Therefore, the integral method of the investigation of this problem must be considered as a most reliable one, since this method accounts the resultant element of the water balance, that is the amount of the runoff from the forest and field watersheds. This method helped to solve many obscure and disputable questions of this problem.

II. The question of the effect of the forest on the total annual runoff is the less clearly one.

The investigations of the small afforestated watersheds in the flat regions of the European part of the USSR have shown the essential (1.5-2 times) decrease of the total annual runoff and spring runoff, as well as of the coefficient of the runoff for the forest watersheds as compared with field watersheds, having the same areas and situated in the similar climatic conditions.

At the same time, the numerous observations for the large and medium rivers of the flat regions of the European part of the USSR have not shown a decrease of the mean annual runoff and of the runoff coefficient for the rivers with afforestated watersheds against the less afforestated ones, showing even some increase of them (10-20 % and more), more noticeable for the rivers in the arid regions. This apparent unconsistency is due to the contribution of the surface runoff to the underground runoff under the influence of the forest soils; the underground water is usually not drained by the shallow beds of the small afforestated watersheds in the flat regions.

It follows from this, that the effect of the forest on the total annual runoff depends (the other conditions being the same) on the river size and the extent of the drainage of the snowmelt and rainfall waters, contributed to the ground waters, by a river bed.

This fact has not been considered, being one of the reasons of the opposite opinions of this question.

III. The observations of the small watercourses in the mountain regions of the Switzerland and the USA have shown, that the total annual runoff in the small forest watersheds as compared with field watersheds (the data, reported by A. Engler) is not changed or there is some decrease of it for 20-30 % (the data reported by Burger, Bates and Henry); this decrease is caused rather by the interception of snow by the forest cover with prevailing fir-trees, than by the increased consumption of water by the forest for the transpiration; it may be also supposed, that some part of the snowmelt and rainfall waters, percolated into the deep aquifers in the forest watersheds, was not accounted.

IV. Owing to a change of the hydrophysical properties of the forest soils under the influence of the forest, and namely, the increased porosity and waterpermeability, the effect of the forest on the regime of the river flow consists mainly in the alteration of the distribution of the runoff throughout the year and the essential increase (by 3-5 times and more) of the low flow due to the decrease of the surface runoff of the snowmelt and rain waters during the floods. The forest stimulates also the essential

decrease of the extreme values of the runoff, the amount of this decrease being dependent on the rain pattern as well as on the river size and the depth of the river bed.

Numerous data, illustrating these statements, and the analytical expressions of the correlation between the decrease of the maximum flow and the percentage of the watershed afforestation are given in the report.

The effect of the deforestation on the long-term variations of the river flow is also considered in the report.

Résumé

1. La question de l'action de la forêt sur l'écoulement total annuel est une des plus discutée. Les recherches sur les petites parcelles forestières dans les régions de plaine de la partie européenne de l'U.R.S.S. ont montré la diminution notable (1,5 à 2 fois) d'écoulement total annuel et de l'écoulement au printemps, aussi bien du coefficient d'écoulement des parcelles forestières que de celui comparé avec les parcelles en plein champs ayant les mêmes surfaces et situées dans les mêmes conditions climatiques.

En même temps, les nombreuses observations pour les rivières grandes et moyennes de la même région de l'U.R.S.S. n'ont pas montré une diminution de l'écoulement moyen annuel et du coefficient d'écoulement pour les rivières avec des bassins forestiers par rapport aux bassins moins couverts de forêts ; elles ont même montré une certaine augmentation (10 à 20 %) et plus) plus notable pour les rivières des régions arides. Cette apparente contradiction est due à la participation de l'écoulement de surface sur l'écoulement souterrain des sols forestiers ; l'eau souterraine n'est pas habituellement drainée par les lits peu profonds de petits bassins forestiers dans les régions plates.

Il en résulte que l'action de la forêt sur l'écoulement total annuel dépend (lorsque les autres conditions restent les mêmes) de l'importance de la rivière et de l'extension du drainage des eaux de fusion et de pluie.

2. Les observations sur les cours d'eau dans les régions de Suisse et de l'U.S.A. ont montré que l'écoulement annuel dans les petits bassins forestiers par rapport aux bassins de pleine campagne n'est pas changé ou bien il y a une certaine diminution de plus ou moins 20 à 30 % ; cette diminution est causée plutôt par l'interception de la neige par le feuillage de la forêt contenant surtout des conifères et non par la consommation plus forte d'eau de la forêt par transpiration ; on peut aussi supposer qu'une certaine partie des eaux de pluie ou de fusion peut s'infiltrer dans les nappes profondes des bassins forestiers.

3. Au sujet d'une modification des propriétés hydrologiques des sols forestiers sous l'influence de la forêt et notamment l'augmentation de la porosité et de perméabilité, l'action de la forêt sur le régime des rivières consiste surtout dans la modification de l'écoulement sur les douze mois d'une année et l'augmentation notable (de trois à cinq fois et plus) du débit d'étiage au détriment de l'écoulement pendant les crues.

La forêt réduit donc les valeurs extrêmes de l'écoulement, le montant de cette diminution dépendra de la répartition des pluies, de l'importance de la rivière et de la profondeur de son lit. De nombreux résultats illustrant ces considérations sont donnés dans le rapport.

L'effet de la déforestation sur la variation à long terme du débit de la rivière est aussi considéré dans le rapport.

The question of the effect of the forest on the regime of the river flow is one of the most disputable problems in the hydrology and the science of forest

The solution of this question is often quite different: some authors are of the opinion, that the effect of the forest on the magnitude and the regime of the river flow is positive, the others say that the forest reduces the river flow and consequently its role is negative.

It is to be noticed, that all of them refer to the equation of the water balance, the latter being consistent in both cases and used as an argument of the quite opposite opinions.

While this question seems to be simple and clear, the problem of its solution is complicated by the variety of factors, affecting the water balance of forest watersheds; besides many experimental investigations of this question have not been perfectly conducted, the separate elements of the water balance being individually and onesided examined on the small plots or even on the monoliths, without taking into consideration the other factors of influence and without a general verification of the water balance of the forest watershed as a whole. So, for instance, the well known investigator P. W. Otozky (5) tried for many years to prove his point of view referring the fact of the lower level of ground water in the forest as compared with the field; but he did not take into account the hydrophysical properties of the forest soils, and namely, the effect of their porosity, waterpermeability and deep drainage of water by the tree roots; these conditions are the reasons why the forest soils as well as sandy soils absorb and conserve the ground water well, while its level is sometimes lower than that in the less permeable field soils. In many investigations the separate components of the water balance have not been taken into consideration accurately and completely enough owing to the imperfection of the measuring instruments. These components are, in particular, the amount of the infiltrated rainfall, its contribution to the ground and underground water, the transpiration and evaporation from the vegetable cover and others.

As a result, some of the important elements of the water balance have not been considered at all or determined not quite accurately and all this led to the opposite conclusions.

The more reliable method of the investigation of this question is an integral one, consisting of the analysis and comparison of the resultative elements of the water balance, that is the amount of runoff in the forest and field watersheds.

The author of this report tries to shed a light on some disputable statements associated with this question, using as a base the investigations of the amount and the regime of the runoff in the forest and field watersheds, carried out in USSR and other countries.

Some questions concerning the effect of the forest on the regime of the river flow will be briefly considered further:

I. The effect of the forest on the total annual runoff.

II. The effect of the forest on the variations of runoff throughout the year and extreme values of runoff.

III. The effect of a deforestation on the long-term variations of the annual river flow.

I. The question of the effect of the forest on the total annual runoff is a less clearly one. The reason is the apparent contradiction of resultative values of runoff for small and large rivers with afforestated watersheds.

Numerous investigations of the small rivers in the flat region of the European part of the USSR, carried out by the State Hydrological Institute and the Research Institute on the Forest Economy of the Soviet Union, show the essential decrease (1.5–2.0 times) of the total annual runoff from the forest watersheds as compared with the field watersheds of the same area, situated in the similar climatic conditions.

So, for instance, the average values and coefficients of runoff for 8 years for the experimental watershed "Tajeshny" afforestated for 98 %, taken from

TABLE I

The average values of rainfall, runoff and coefficient of runoff for the watersheds "Usadjevsky" and "Tajeshny"

(Waldai Research Hydrological Laboratory, forest zone)

Name of watershed	Water-shed area km²	Af-fores-tation %	The average values for the period 1949-1956		
			rain-fall mm.	run-off mm.	coefficient of runoff
Usadjevsky	0.36	98 %	669	359	0.54
Tajeshny	0.45	3 %	792	215	0.27

NOTE. The watershed "Usadjevsky" consists of arable land and meadow. The percentage of bogs is 16. The watershed "Tajeshny" is covered with the coniferous forest in age of 50-70 years. The fir-trees prevail.

the records of observations, carried out in the Waldai Research Hydrological Laboratory of the State Hydrological Institute (forest zone) (10), is 1.5-2.0 times less than the respective values of runoff for the nearest field watershed "Usadjevsky".

The average values for 10 years (1947-1956) for the spring runoff and coefficients of spring runoff for the experimental watershed "Vorony" with the percentage of the afforestation 90 %, taken from the records of observations for the small watercourses of the Runoff Station "Pridesnjanskaja" are 1.84 times less than that for the experimental watershed "Petrushino" with the percentage of the afforestation 33 (table 2).

The quated data and numerous other date of observations, carried out in the small forest watersheds of the Research Institute on Forest Economy of the Soviet Union, show clearly the essential decrease of the amount of the runoff for the small forest watersheds as compared with the field watersheds.

But what is the reason for this decrease? The most of the investigators were of the opinion, that the decrease of the amount of the runoff for the small forest watersheds as compared with the field watershed is due to the transpiration increased by the forest cover, and consequently the theory of the drying effect of the forest seemed to be confirmed.

The observations, carried out for the large and medium rivers of the European part of the USSR however, give a quite opposite evidence.

So, for example, A. P. Bochkov (1) investigated the correlation between the runoff and rainfall for 92 large and medium rivers of the European part of the USSR with the areas of river basins from 300-1000 km² to 100 000-200 000 km², with a different percentage of their afforestation, using the records of the longterm observations (from 4-5 to 56 years); he concluded that the average amount of the runoff increases, with the increase of the percentage of the afforestation, for 10-20 % in the forest zone and 20-40 % in forest-steppe and steppe zone, the total annual rainfall and the water equivalent of snow cover being equal in all cases.

TABLE II

The average values of the water equivalent of snow cover, depth of spring runoff and coefficient of spring runoff for the watersheds "Vorony" and "Petrushino"

(Runoff Station "Pridesnjanskaja"; forest-steppe zone)

Name of watershed	Water-shed area km^2	Af-fores-tation	The average values for the period 1949-1956			Note
			The water equivalent of snow cover mm.	The depth of spring runoff	The coeffi-cient of spring runoff	
Petrushino	1.2	33	125	70	0.56	The foliage forest
Vorony	1.1	90	136	38	0.29	prevails in both water-sheds

L. M. Sidorkina (7) made a similar conclusion, but she used a slightly different method, and namely, the method of the comparison of the values of runoff for 16 pairs of chosen river basins of the European and Asiatic parts of the USSR with long-term series of observations; the river basins had the similar areas, were situated in similar climatic conditions but had a different percentage of the afforestation. From these data it was found, that the average value of total annual runoff for the equal periods of observations for more afforestated river basins exceeds (15 of 16 cases) the average value for less afforestated basins for 10-30 %; it exceeds also the value of runoff for the whole region, as presented in the isohyetal map of runoff; it was found also that with a difference of values of total runoff for well afforestated basins, as compared with the less afforestated basins, the proportion of the overland runoff in the annual runoff decreases and the proportion of the underground runoff in the annual runoff significantly increases.

These numerous data show that the decrease of the overland runoff for the rivers with afforestated watersheds is compensated by the increase of the underground runoff for the large and medium rivers, when the depth of river beds being sufficient for the drainage of the ground water of that basin. In the small forest watersheds, however, with a little depth of a river bed, usually occurring in flat regions (the little depth of a river bed being associated with the low overland runoff) this compensation does not take place, since the snowmelt water and rainfall, percolated through the soil, are not being drained by the shallow beds in these watersheds; as a result, the total annual runoff decreases significantly.

Consequently, the decrease of the runoff for the small forest watersheds, as compared with field watersheds, is caused not by the increased consumption of water by the forest, but by the intensive infiltration of the rainfall and snow-melt waters by forest soils and the contribution of the overland runoff to the underground runoff, which the shallow river beds of those watersheds being not able to drain.

As a result, one very important element of the water balance was not accounted in the analysis of data for such watersheds, and namely—the infiltration of the rainfall and snow-melt waters and contribution to the ground water, and all this led to the faulty conclusions.

The increased or at least unchanged total annual runoff in the forest watersheds may be explained by the fact, that the increased water consumption for the transpiration and evaporation from the vegetable cover is compensated by the decrease of the evaporation from the soil under a forest cover in conditions of a sufficient humidity.

These assumptions are ascertained by the observational data of the Swiss Experimental Station.

According to these data, analysed and reported by A. Engler (13), the average value of the total runoff for 13 years (1903-1915) for the experimental watershed "Sperbel", afforestated almost wholly, is 83 mm or 7,8 % less as compared with that for the experimental watershed "Rappen" with the percentage of forest 33.

Both experimental watersheds are situated in the North foot-hills of Alps at height 900-1200 m in the zone of the precipitation amounting to 1500-1600 mm; the beds of these mountain water-courses are deep enough to drain wholly or almost wholly the ground and underground waters of that watershed.

But the decrease of runoff for the experimental watershed "Sperbel", wholly afforestated, is to a great extent due to the smaller amount of precipitation (1589 mm for the experimental station "Sperbel" against 1657 mm for the experimental station "Rappen").

Taking into consideration this condition as well as a little difference in heights of both watersheds and a little additional afflux of ground water in the experimental watershed "Rappen", A. Engler concluded, that the average coefficient of runoff may be assumed to be equal 0,60 (in the practical limits of accuracy), being the same for both watersheds with a following distribution of the elements of the water balance in the forest and field:

	Forest	Field
Runoff	60 %	60 %
Evaporation from a vegetable cover	15 %	10 %
Transpiration	20 %	6 %
Evaporation from soil	5 %	24 %
total	100 %	100 %

According to these data, an increased loss for the evaporation and transpiration in the forest is compensated by the decreased evaporation from soil and, as a result, the total loss for evaporation and transpiration is the same for the forest and field.

It is to be noted, however, that these investigations refer to the zone of an excessive humidity with the amount of the annual precipitation about 1600 m.

In arid regions, where the evaporation from soil increases significantly and the temperature conditions in forest and field are more contrasted, the results of the comparison would be another and the total evaporation from soil in field could exceed the total evaporation in forest; this assumption is ascertained by the increase of the resultative element of the water balance of the runoff value for the forest watersheds against the field ones in the conditions of the steppe zone.

The data, reported by Burger (12), who continued the investigations initiated by A. Engler in the experimental watersheds "Sperbel" and "Rappen", are somewhat contradicting the conclusions made by A. Engler.

According to these data, the average value of the runoff coefficient for the experimental watershed "Sperbel" for the period of 25 years (1927/28-1951/52) is 0,47 against 0,59 for the experimental watershed "Rappen"; that is the runoff coefficient for the forest watershed is 20 % less against the partly deforestated watershed "Rappen", but the evaporation coefficient is 29 % higher.

From these data Burger concluded: "Forest consumes, no doubt, more water, than meadows and pastures".

However, the analysis of the distribution of the precipitation, runoff and evaporation over the seasons for both watersheds (9) shows, that the difference in the amounts of runoff and evaporation for the afforestated and partly deforestated watersheds refer mainly to winter-spring months, when forest consumes little water. The difference in the values of total evaporation for 3 months amounts only 13 %. It may be supposed, therefore, that the decrease of the runoff in the afforestated watershed "Sperbel" is not due to the increased consumption of water by forest, but caused by other factors, in particular by the interception of snow by the forest cover with the prevailing fir-trees in these watersheds; this assumption is ascertained by the experimental investigations conducted in USA (II); the reason may lay also in the fact, that snowmelt and rainfall waters, percolating through the forest soils into the deep aquifers, are not completely drained by the watershed "Sperbel".

So, the integral investigation of the effect of the forest on the total annual runoff shows, that in the flat regions of the European part of the USSR the total runoff is not decreased and even somewhat increased under the influence of the forest, this increase being more noticeable in the arid regions of the forest-steppe and steppe zone. In mountain conditions of the excessive humidity the forest does not modify the total runoff at all (the data reported by A. Engler) or somewhat modifies it (the data reported by Burger, Bates and Henry); this effect being not exclusively because of the increased transpiration in forest, but mainly because of the interception of snow by the forest cover, as may be supposed, because some part of the snowmelt and rainfall water, running under the ground, was not accounted. It was found also, that the effect of the forest on the total annual runoff depends

(the other conditions being the same) on the size of the water-course and the extent of the drainage of groundwater by the water-course from its basin.

II. The question of the effect of the forest on variations of the runoff throughout the year is a most clearly one.

Owing to the change of the hydrophysical properties of the soil under the influence of the forest and namely the increase of its effective porosity and waterpermeability as well as the vertical drainage of water by tree roots, the forest contributes a significant part of the surface runoff of snowmelt and rainfall waters to the soil and ground water runoff.

As a result, the forest stimulates a significant increase of the low runoff on account of the surface runoff of snowmelt and rainfall water, that is it distributes the runoff throughout the year more evenly. This fact is ascertained by the numerous data of observations for rivers in the European part of the USSR with a different extent of the afforestation of their basins. So, for instance, the average specific runoff of the summer months for the period of 12 years (1935-1946) for the river basin "Voria" afforestated for 70 %, is 2,4 times higher than that for the river basin "Sit" afforestated for 3 %, and for the winter months is almost 4 times higher.

Both river basins are situated in the basin of the Upper Volga in the similar climatic conditions, their drainage areas being almost equal (table III).

TABLE III

River	Point	Drainage area km²	The period of observations	The afforestation %	The average specific runoff, l/sec. from 1 km²	
					for VI-IX	for XII-II
Voria	Kablukovo	887	1935-	70	3,64	2,72
Sit	Rodionovo	860	1946	3	1,53	0,72

According to the data, reported by L. M. Sidorkina, for other pairs of the chosen experimental watersheds with a different percentage of the afforestation, situated in the forest zone of the European part of the USSR, the average specific runoff for summer months, for the equal periods of observations, are 7-80 % higher for the well afforestated watersheds than that for the less afforestated watersheds (the percentage depending upon the extent of the afforestation); for the winter months the same value is II-97 %.

For 5 pairs of the watersheds in the forest-steppe and steppe zone of the European and Asiatic parts of the USSR, the increase of the specific runoff for summer and winter months for the equal periods of observations, according to the same data, amounts from 7-10 %, with a little difference of the afforestation, to 200-300 % with a significant one.

With the increase of the specific runoff for the forest watersheds, the maximum specific runoff and volumes of the spring and rainfall floods are significantly decreased, this decrease being dependent not only on the rain

pattern, stimulating a flood (a rain of a short duration or a prolonged one, saturating the forest soil) and on the forest type, but on the basin size too.

For the small watercourses with not deep beds, which do not drain a significant part of the ground water, the decrease of the maximum specific runoff is more pronounced than that for the large and medium rivers, draining the ground water from their basins. So, for example, the average spring specific runoff for 9 years of observations, for the experimental watershed "Tajeshny", afforestated for 98 %, is 8 times less as compared with the experimental watershed "Usadjevsky" with an insignificant percentage of the afforestation, and the depth of the runoff being 1,5 times less.

The average values of the maximum spring specific runoff for the experimental watershed "Vorony", afforestated for 90 %, is 40 % less than for the watershed "Petrushino", afforestated for 33 % and the volume of the spring runoff being 2 times less (table IV).

TABLE IV

Name of the watershed	The drainage area km²	The afforestation %	The average values		Note
			of the maximum spring specific runoff l/sec. from I km²	of the depth of spring runoff in mm.	
		Waldai Research Hydrological Laboratory.			
Usadjevsky	0,36	3 %	1085	120	For the periods 1939-1940 and 1948-1954 in total 9 years.
Tajeshny	0,45	98 %	141	82	
			The Runoff Station "Pridesnjanskaja".		
Petrushino	1,2	33 %	435	70	For the period 1947-1956, in total 10 years.
Vorony	1,1	90 %	264	38	

The decrease of the maximum discharges of floods caused by the rain for the experimental watershed "Vorony", as compared with the maximum discharge for the experimental watershed "Petrushino", is more pronounced, being 0,10-0,15. The flood in the forest watershed is more stretched and routed (fig. I) owing to the more significant absorption of the rain water by the forest soil.

For the mountain watercourses, according to the data, reported by A. Engler, the coefficient of the decrease of the maximum discharges and volumes of floods, caused by the rainfall, under the influence of the forest amounts 0,4-0,7, when the river beds are relatively deep, that is it is decreased by 1,5-2,5 times; when the rains are prolonged, causing the saturation of the forest soil, the decrease is less or it is absent at all.

It may be seen from this, that when the rains are prolonged, the storage capacity of the forest soils decreases significantly and its effect on the decrease of the maximum floods, caused by the rainfall, is less.

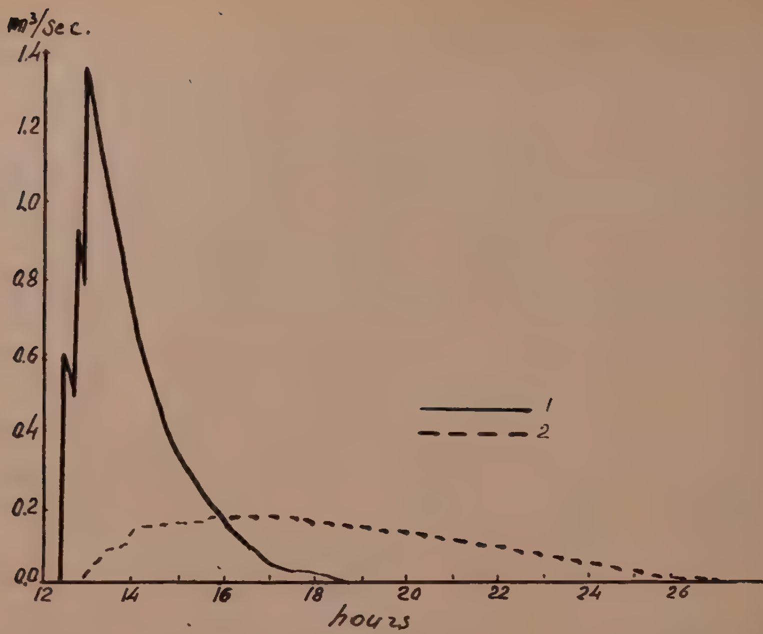

Fig. 1 The progress of the flood, caused by rainfall, in the gullies of the Runoff Station "Pridesnjanskaja".
1. — Petrushino (afforestation 33 %, F = 1.2 km^2)
2. — Vorony Yar (afforestation 90 %, F = 1.1 km^2)

In regard to the effect of the forest on the decrease of the maximum spring floods for the large and medium rivers of the European part of the USSR, the analysis of the question for the long periods of observations of 76 drainage basins in the forest zone with areas amounting from 200 to 170 000 km^2 shows (2), that this decrease subordinates to the linear low and can be expressed as:

$$\delta = 1{,}0 - Kf \tag{I}$$

where

δ — the coefficient of the decrease

f — the afforestation of the drainage basin in proportion from 1,0.

K — the coefficient variable for the rivers of the forest zone from 0,60 for the basin of the Upper Volga, to 0,73 for the rivers of the North regions of the European part of the USSR with prevailing fir-tree forest.

For rivers of the forest-steppe and steppe zone, the decrease of the maximum spring floods under the influence of the forest is more pronounced and may be analytically expressed by the semilogarithmic relation of the following form (8):

$$\delta = 1{,}0 - K_1 \lg (1 + f),$$

where the value of K_1 varies from 0,25 for the clay and loamy soils, covered with a forest, to 0,35-0,45 for the sandy soils under the forest.

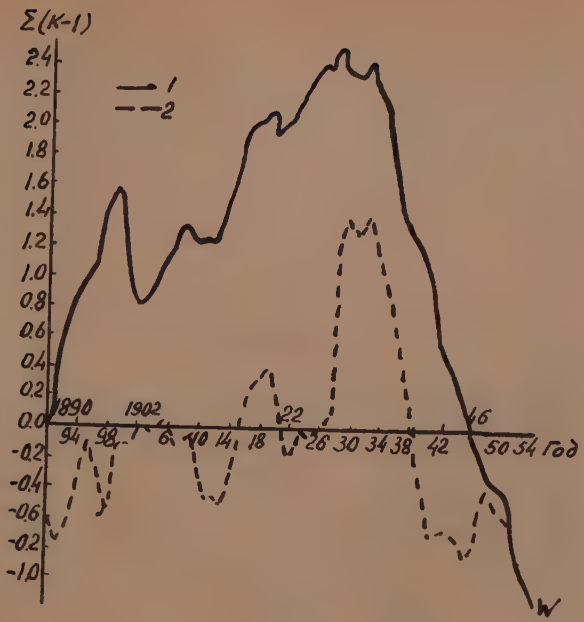

Fig. 2 The integral curves of the deviation from the average value.
1. — The annual flow of the river Volga at Kujbishev.
2. — The number of days with the West type of circulation.
K — The relation to the average value.

The data, shown above, ascertain the significant effect of the forest and forest soils on the variations of runoff throughout the year and on the extreme values of the runoff; the magnitude of this effect depends on the river size, depth of its bed and the extent of the drainage of ground and underground waters in that basin, the other conditions being the same.

This fact, being of the great importance in regard of the total runoff, as well as variations of the runoff throughout the year and extreme values of the runoff, was not accounted to the sufficient extent by many investigators, being the reason, with some other ones, why the question of the effect of the forest on the regime of the river flow has been so disputable.

In conclusion it is necessary to say some words regarding the effect of the deforestation on the long-term variations of the river flow.

As it is known, this question has also raised a numerous literature with a contradictory reasoning (see, for instance, [I, 4, 6, 14, 15]). From the data, given above, regarding the effect of the forest on the variations of the runoff throughout the year and on the total annual runoff, it may be concluded, that the deforestation and the subsequent change of the hydrophysical properties of the soil affect the low runoff and the total annual runoff, but with a different extent and even in a contradictory way, this fact being one of the reasons of the controversy of the opinions on this subject.

From the considerations, explained above, it follows, that the deforestation of the drainage basins can significantly (by several times) decrease the amount of the low runoff, not changing essentially the total annual

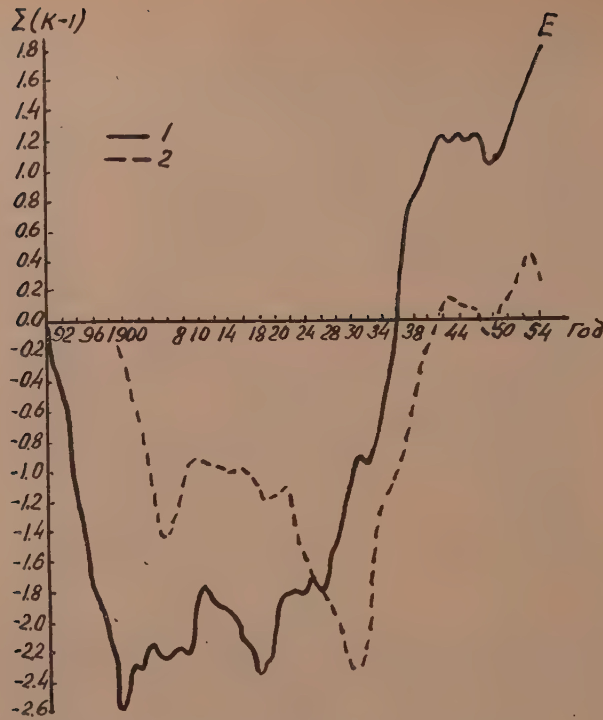

Fig. 3 The integral curves of the deviation from the average value.
1. — The annual flow of the river Angara at Pashka.
2. — The number of days with the East type of circulation.
3. — The relation to the average value.

runoff, since in the same time the surface runoff of the spring and rain floods increases. It means that the deforestation augments mainly the unevenness of the distribution of the runoff throughout the year, but does not change the total annual runoff, the variations of the latter being governed, in general, by variations of the climatic factors (in particular in zone of the sufficient humidity).

This fact may be illustrated more apparently by the comparison of the long-term variations of the river flow with variations of the patterns of circulation of the air masses. The figures 2 and 3 show the long-term variations of the river flow of the Volga and the Angara and the long-term variations of days with the West and the East patterns of the air mass circulation, according to A. A. Girs (3), both being expressed in the form of the integral curves of the deviation from the normal value. The figure 2 shows, that the long-term variations of the river flow of the Volga at Kujbishev are consistent with a sufficient degree of the accuracy with the long-term variations of days with the West pattern of the air mass circulation (type W) and the long-term variations of the river flow of the Angara are consistent more accurately with the long-term variations of days with the East pattern of the air mass circulation (type E).

It appears, that the effect of the deforestation on the total annual runoff (if there is any) is so little against the great influence of the climatic factors on the variations of the river flow, that it can not be determined with a practical degree of accuracy and separated in an evident way. From the above considerations it follows also, that the deforestation (and the subsequent change of the hydrophysical properties of the soil) of the small watercourses, which do not drain the ground water from their basins, can even cause the significant increase of the total annual runoff at the expense of the increase of the surface runoff and the decrease of the proportion of the underground water, which was not drained before by the shallow beds of these watercourses.

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PHYSICAL CONDITIONS OF SNOW THAWING AND SPRING DRAINAGE IN AND OUTSIDE THE FOREST AS OBSERVED IN THE ENVIRONS OF MOSCOW

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Summary

Following influences of forests are established in relation to snow melting intensity and to volume of waterdischarge.

1. Forests intercept by their cover short-wave and long-wave radiation; this is the main physical feature of forests in the formation of the thermal and water regime in forest areas. In result of radiation losses in the cover, the mean intensity of snow melting in forests is twice lower than the melting intensity in open areas; snow melting duration is consequently twice longer. Snow melting in forests ends 10-15 days later than in fields and this is under higher air temperature.

2. In behalf of the looseness of forest soils and of an additional water capacity, water discharge in forests takes place mainly inside the soil and the forest litter. Water discharge inside the soil litter, and crops out and is here a pure superficial water flow in a thin layer.

3. The forest cover moderates at night-time and during frosts the cooling and freezing of water in the snow and in soils; this is why water discharge in forests is more even during 24 hours. The water discharge moduli are smaller in forests, whereas the duration of infiltration is longer than in fields.

Combined influence of forests physical conditions creates noticeable features of water discharge and development of spring high waters in time: during day-hours the water discharge in forests is smaller than in fields, during night-time greater. The range of water consumption in a forest basin is smaller than in an open one—discharge is regulated in forests. Due to a smaller snow melting intensity, better conditions for infiltration are created in forests. The peak of spring high waters in forests in relation to the peak of spring high waters in an open basin is put off for 9 days.

Finally, coefficients of spring water discharge in forests compared with coefficients of water discharge in an open basin are smaller by 1.2-5 times because of a lowering of the intensity in snow melting as a result of radiation losses in the forest cover, and by 1.3-2 times as a result of the regulation capacity of forest soils, along with heatinsulating influence of the cover.

Résumé

Les influences exposées sont celles en rapport avec l'intensité de la fusion de la neige et avec le volume de l'écoulement.

Les forêts interceptent les radiations à courte et à grande longueur d'onde. Il en résulte que la fusion de la neige est deux fois plus lente en forêt : cette fusion finit de 10 à 15 jours plus tard en forêt.

En forêt, l'eau pénètre dans le sol poreux de la surface pour en sortir comme un écoulement superficiel de faible épaisseur.

Le couvert de la forêt modère le refroidissement et la congélation de l'eau de la neige et du sol pendant la nuit, ce qui rend plus uniforme l'écoulement de la forêt au cours des 24 heures d'une journée. Le module de l'écoulement est plus petit en forêt par suite de la plus longue durée d'infiltration.

Il en résulte que les hautes eaux de printemps ont un débit plus faible en forêt pendant le jour, mais plus élevé pendant la nuit par rapport à l'écoulement en pleine campagne. L'amplitude des variations de l'écoulement d'eau en forêt est plus faible qu'en pleine campagne — la forêt régularise le débit.

Par suite de l'intensité plus faible de la fusion, de meilleures conditions d'infiltration se produisent en forêt. Le maximum des hautes eaux est reculé de 9 jours en forêt par rapport à la pleine campagne.

Finalement, par rapport à la situation en pleine campagne, les coefficients d'écoulement des eaux de printemps en forêt sont réduits de 1,2 à 5 fois par suite de la diminution de l'intensité de fusion de la neige et de 1,3 à 2 fois par suite de la capacité régulatrice des sols.

I. Local conditions

The paper is based on observations carried out at the Istra Station of the All-Union Research Institute of Sylviculture and Mechanization of Forest Economy during the period from 1938 to 1958 (with an interval of about 10 years), at the Moskva-Volga watershed, 70 km north-west of the city of Moscow.

Annual precipitation in the district amounts to 584 mm, the average annual temperature of the air being 3.3 °C with the following monthly distribution:

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1. Precipitation, mm	33	29	33	32	44	69	85	65	56	52	43	43
2. t° av.	—10.5	—10.0	—5.4	3.4	11.4	15.0	17.4	15.4	9.9	3.8	—2.4	—8.2
3. t° max.	4	5	14	24	31	31	36	37	32	23	12	7
4. t° min.	—53	—39	—36	—24	—8	—4	2	—2	—7	—21	—28	—40

Two periods may be distinguished from the point of view of the thermal and moisture conditions in the district:

1. Period of intensive water consumption, April to September, inclusively, i. e. the period of the vegetation of the forest and the agricultural crops. The radiation balance is positive at this time. In April-May part of the snow water flows down the surface (high-water), another part of it replenishes the moisture reserves in the soil and the ground, then the water accumulated in the soil and arriving as precipitations is consumed by evaporation and transpiration due to the abundant influx of heat.

In June-July the radiation balance achieves its peak of about 7 kcal cm^{-2} mo., thus ensuring evaporation of the bulk of the summer precipitation.

2. Period of moisture accumulation, October to March, inclusive.

In this period the radiation balance is either close to zero or negative, evaporation is insignificant owing to the lack of heat, the water accumulates on the surface of the soil as snow and ice; the water reserves in the soil and the ground are partly replenished.

According to the average data for many years, during the cold half-year snow precipitation amounts to about 170-180 mm. 10-year observations at the Station revealed that by the commencement of thawing, late in March, about 150 mm of water as snow is left in the field (with fluctuations from 97 to 190 mm) and about 140 mm in the forest (with fluctuations from 85 to 186 mm); the rest is lost by evaporation from the snow surface and the tree crowns.

The mantle (deluvial) loams comprise the soil-forming ground in the massive where the drainage basins are located.

In areas with slopes of 0.05-0.15 the soils in the forest basin are predominantly medium podsolous-loamy, while in areas with slopes of less than 0.05 they are highly podsolous-loamy, both being but slightly gleyey.

The field soils are also medium podsolous-loamy, but washed out practically everywhere; in areas with slopes exceeding 0.1 they are strongly washed out. The soils on slight slopes in the field basin are highly podsolous.

The soils of the forest and the field basins are equal with respect to water-permeability and moisture, capacity of the one-metre layer, but they differ in the looseness of the upper layer: 0-40-50 cm; the volumetric weight of the forest soils at the A and B_1 horizons varies from 1.0 to 1.5 gm cm^{-3}, and in the field, from 1.20 to 1.57 gm cm^{-3}.

Due to the fact that the tree roots greatly loosen the forest soils, the latter possess an additional water capacity of about 400 m^3 ha^{-1} in the upper half-metre layer as compared with the field soils. This additional capacity will be referred to as the "regulatory" capacity of the forest soils.

In the lower half of the one-metre layer the volumetric weight, the porosity, and the water-permeability of the forest and field soils are identical.

The method of field monoliths (soil columns in 1 m^2 cross section isolated on all sides) enabled us to establish the average summer filtration consumption beyond the one-metre layer which proved to be 4 (1 ± 0.24) 1 per half-hour when the soil temperature was about 10 ° in the forest and about 15 ° in the field. (N. F. Sozykin, 1940), and therefore the soils of the drainage reservoirs were placed in the category of medium-permeability soils.

The drainage reservoirs (the forest reservoir occupies 23.6 ha, the semi-forest reservoir, 19.4 ha and the field reservoir, 30.9 ha) make up a single massive covering the ravine heads and the slopes of the flat elevation common for all the reservoirs.

The watersheds between the drainage reservoirs are slightly inclined and include occasional small and partly swamped depressions with an area of 0.5—2.0 ha.

The forest basin is characterized by the predominance of loamy fir forest of the composition: 7 firs, 2 birches, 1 asp, rare oak of the IVth age group with an average density of 0.8 and wood reserve of 270 m^3/ha (46 %) similar to, but somewhat sparser than fir forests with a density of 0.5—0.7 and a wood reserve of 180—230 m^3/ha (19 %), followed by mixed fir and leaf-bearing forests consisting predominantly of birches and asps of the VIth age group with a density of 0.7—0.85 and a wood reserve of 220—260 m^3/ha (11 %) and overgrown cleared spaces of the same composition with a density of 0.8 (14 %).

Glades and roads take up 10 %. Thus, 90 % of the forest basin area is actually covered with forest.

The average slope of the basin is 0.0015, the exposure is SW.

In the open basin the slopes are ploughed (42 %), the flat near-watershed part at the heads and the bottoms of the ravines are occupied by meadows, the eastern part near the watershed is occupied by meadows with forest patches comprising an area of 13 %. The average slope of the basin is 0.0002, the exposure is SE.

II. Snow thawing

Snow thawing in and outside the forest begins simultaneously in late March-early April with the passage of 0° by the average air temperatures,

but proceeds with varying intensity. The average duration of thawing in the field is 17 days and in the forest about 30 days, the average thawing intensities in the field being about 9 mm day^{-1} and in the forest, about 5 mm day^{-1}.

Table 1 exhibits factual data on the conditions and duration of snow thawing during the last three years in the forest basin and in the open.

As a result of the lower intensity, the termination of snow thawing in the forest shifts to the period when the temperature of the air and the radiation are high. The average annual temperature of the air for the period of thawing in the forest is at all times higher than the average temperature for the period of thawing outside the forest, while the temperature of the air during the period of the thawing of the snow remainder in the forest is appreciably higher.

If we break up the period of snow thawing in the forest into two parts, the first being simultaneous with the thawing in the field and the second covering the thawing of the snow remainder in the forest after the disappearance of the snow in the field, then the intensity of snow thawing in the forest during the second period will be 1.5—2 times as high as during the first period and will approach the average intensity of snow thawing in the field. The reason for the slower snow thawing in the forest is the interception of short-wave radiations by the tree crowns and the cover and the insufficient supply of long-wave radiation for the thawing of the snow under the cover as compared with the field. Because of this the high-water peak in the forest lags behind that in the open basin, on the average, by 9 days with variations from 2 to 25 days.

As is well known, for the same reason, evaporation from the snow surface under the forest cover is 4 to 5 times as low as in the field in winter

TABLE I

Physical conditions of snow thawing: Duration and average thawing intensity in forest and field

	1956		1957		1958	
	field	forest	field	forest	field	forest
Date on which average daily temperature of air passed 0°	7. IV		29. III	7. IV		
Snow reserves at commencement of thawing, mm of H_2O layer	156	147	165	144	181	166
Average dates of snow thawing termination	22. IV	30. IV	12. IV	23. IV	22. IV	27. IV*)
Thawing duration, days	16	24	15	26	16	21

*) Rainfall on 26. IV accelerated snow thawing in the forest. Therefore the subsequent calculations are based on the period from 7. IV to 22. IV.

	1956		1957		1958	
	field	forest	field	forest	field	forest
Amount of snow which had thawed simultaneously with that in field, mm	—	80	—	—	—	85
Average thawing intensity, mm $days^{-1}$	9.8	5.9	11.0	5.5	11.8	5.3*)
Total radiation for period from moment when average daily temperatures passed 0° to moment of thawing termination, cal cm^{-2}	2898	7004	3908	6914	4134	—
Average daily radiation for period of thawing in field, Q cal cm^{-3} day^{-1}	181	—	261	—	258	—
Average daily radiation for period of thawing in forest, cal cm^{-2} day^{-1}	—	292	—	266	—	—
Same, for period after drainage termination in field up to drainage termination in forest, Q cal cm^{-2} day^{-1}	—	513	—	273	—	—
Sum of positive temperatures for thawing periods, degs.	55.8	109.4	30.6	84.5	50.5	—
Average daily temperature for the thawing period in field, degs.	3.5	—	2.0	—	3.2	—
Same for thawing period in forest	—	4.6	—	3.2	—	—
Average daily temperature for period of thawing of snow remainder in forest, after disappearance of snow in field	—	6.7	—	4.9	—	—
Spring drainage coefficient	9.56	0.10	0.88	0.46	0.65	0.44
Drainage coefficient for period from 7. IV to 22. VI, 1958	—	—	—	—	0.62	0.22

and 3 times as slow in spring and summer (A. A. Louchshev, 1940). For that very reason, again, the heat influx into the ground under the forest cover is 3 to 4 times as low as in the field, and therefore the summer soil temperature in the forest is substantially lower than in the field.

Now we write down the radiation and thermal balance equations for the thawing period:

$$R = \Sigma Q (1 - \alpha) - I \qquad (1)$$

$$R = LE + P + A \qquad (2)$$

By equating them we find

$$\Sigma Q (1 - \alpha) - A = \alpha E + P + I \qquad (3)$$

where ΣQ $(1-\alpha)$ is the sum of the absorbed short wave (total) radiation taking into account the albedo (α) of the surface of the tree crowns or that of the field.

A = heat influx into the soil; in our case, heat consumption for snow thawing (80 cal gm^{-1}, 8 cal mm^{-1} of H_2O layer).

LE = heat consumption for evaporation of E mm of water at latent evaporation heat of L $calgm^{-1}$.

P = heat flux due to the turbulent heat conduction of the layer of the atmosphere adjacent to the earth's surface.

I = effective radiation, i. e. the difference between the influx and consumption of heat due to the radiation of the underlying surface and the back radiation of the atmosphere.

In 1956 and 1958 observations of the radiation and the snow thawing intensity were carried out a) on a glade where the snow albedo was 60 %, b) in a 100 % fir forest where the cover albedo was about 10 % and where 5 % of short-wave radiation penetrated under the cover, and c) in a mixed plantation consisting predominantly of firs, where the cover albedo was about 15 % and where 17 % of total (short-wave) radiation penetrated under the cover.

Table 2 demonstrates the results of these observations with respect to the total radiation, EQ, received on the dates mentioned by the open area and by the cover surface from the commencement of thawing, the amount of snow which had thawed on the glade and on the plantations, and the quantities of short-wave radiation that penetrated under the plantation cover.

Substituting the numerical values quoted in the left part of the table into Eq (3), we find for the glade in 1956

$$2247\ (1-0.6) - 8 \times 101 = 91 = (LE + PI)\ \text{glade} \qquad (3A)$$

for the fir forest

$$2247\ (1-0.1) - 8 \times 19 = (LE + P + I)\ \text{fir} \qquad (3B)$$

for the mixed plantation

$$2247\ (1-0.15) - 8 \times 19 = 1658 = (LE + P + I)\ \text{mixed} \qquad (3C)$$

Substracting (3B) from (3A), and (3C) from (3A), we find

$$(LE + P + I)\ \text{glade} - (LE + P + I)\ \text{fir} = -1779\ \text{cal cm}^{-2} \qquad (3D)$$

$$(LE + P + I)\ \text{glade} - (LE + P + I)\ \text{mixed} = -1567\ \text{cal cm}^{-2} \qquad (3E)$$

The effective radiation (I) and the turbulent heat flux (P) from the fir forest cover into the atmosphere exceed those on the glade by 1779 cal cm^{-2},

TABLE II

Snow thawing and total radiation on glade and under plantation cover

Date	ΣQ	Amount of snow thad had thawed on glade, mm.	Fir forest 5 % penetrated under cover ΣQ cal/sq.cm.	Amount of thawed snow mm.	Mixed forest 17 % penetrated under cover ΣQ cal/sq.cm.	Mixed forest Amount thawed snow mm
1956 / 18. IV	2247	101	112	19	382	19
1958 / 15. IV	1743	84	87	18	297	28
19. IV	3237	166	162	29	552	46

while the effective radiation and the turbulent heat flux from the mixed forest cover exceed them by about 1567 cal cm^{-2}, as it is known from two-year observations that the evaporation under the cover of these plantations is essentially lower than that in the field.

The heat losses estimated by using Eqs. (3A, 3B, 3C), approximate the losses of short-wave radiation in the cover as established by actinometric observations, and deviate from the latter within $\pm$ 10 %.

Indeed, the above calculations show that the fir canopy received 2247 (1—0.1) = 2022 cal cm^{-2}, and 113 calories penetrated *under the cover;* hence, 1909 calories were lost.

The cover of the mixed plantation received 2247 (1—0.15) = 1810 cal cm^{-2}, and 382 cal cm^{-2} penetrated *under the cover;* hence, 1428 cal cm^{-2} was lost which is close to the values calculated above.

Similarly we find for 1958:

	Heat losses in forest based on snow albedo, cover albedo and amount of thawed snow, cal cm^2	Losses of short-wave radiation in cover based on actinometric determinations cal cm^{-2}
	1	2
7—15. IV, 1958		
1. In air forest	1400	1482
2. In mixed forest	1234	1186
7—19. IV, 1958		
1. In fir forest	2714	2751
2. In mixed forest	2406	2189

In the final analysis, the losses calculated by the type 3 equations coincide with the actually found losses of short-wave radiation in the cover, with slight deviations within the errors in estimating the snow reserves, the total radiation, the snow and cover albedos and the radiation under the forest cover.

On these grounds we conclude that the *delay interception of the short-wave radiation in the forest cover is a basic physical property of the forest and the principal cause for retardation of thawing (and of the decrease in the draining volume, which will be discussed below).*

The snow losses by evaporation from the crowns, the radiation losses and the retardation of thawing of the snow under the cover depend on the composition, age and density of the plantation.

Table 3 contains data on the snow reserves in various plantations and the intensity of its thawing as compared with the reserves and thawing intensity on the glades.

The magnitude of the snow reserves at the moment of thawing directly affects the scope of the spring drainage, as we shall see later—the reduction in thawing intensity on medium-permeability soils promotes infiltration and diminishes the drainage coefficient in the forest as compared with the field.

TABLE III

Comparative characteristics of various plantations with regard to maximum snow reserves towards spring, and to thawing intensity

(As revealed by mass observations in 1938, 1939 and 1940 carried out by Z. I. Kuznetsova, S. I. Murashova and V. I. Rutkovsky).

Plantations	Maximum snow reserves toward spring relative to maximum reserves on glades	Intensity of snow thawing as compared with thawing on glades taken as a unit
1. Fir, high-density, third age group and older	0.71—0.75	0.41—0.50
2. Fir, medium-density, third age group and older, and leaf-bearing trees with second fir row of medium density	0.81—0.85	0.51—0.60
3. Pine, third age group and older medium and high density	0.76—0.80	0.61—0.70
4. Leaf-bearing-fir (mixed), high-density, third age group and older, as well as pine saplings	0.81—0.90	0.81—0.90
5. Oak, third age group and older	0.86—0.95	0.51—1.00
6. Soft leaf-bearing and oak saplings, cleared spaces, glades.	0.96—1.05	1.01—1.20

Spring runoff in the forest basin begins, on the average, 3 to 4 days later than in the field basin. In the presence of an ice crust and when the soil is very moist the runoff in and outside the forest begins almost simultaneously. The termination of runoff in the forest basins lags behind, on the average, by 8 days, with variations from 3 to 16 days.

At the beginning of thawing the water saturates the soil unless the surface of the soil is covered with ice. If the thawing intensity, S mm sec^{-1}, exceeds the infiltration intensity, v mm sec^{-1}, then after saturation of the soil there appears a runoff whose layer and modulus, M, are determined by the difference S—U.

The field runoff proceeds chiefly over the surface of the soil, and in the forest, on the greater part of the area, mainly inside the soil and in the forest litter. The near-surface drainage from microelevations in the forest wedges out in microdepressions and microgrooves towards the surface and represents a thin layer of purely surface drainage.

Observations made in the Spring of 1938 (V. A. Troitsky, M. N. Zhernova, 1939) showed the coefficient of the spring runoff on the forest runoff areas to be 0.01, whereas the runoff factor from the forest basin is 0.24. The clay barriers restricting the runoff areas were cut into the soil at a depth of 5 cm, and consequently the major part of the water was drained off from the areas under the barriers, inside the soil.

At the same time the runoff factor on the field areas was 0.65, that from the field basin being 0.94, which indicates that the water in the field was drained chiefly over the surface.

Fig. 1 is a plan of the forest runoff basin with contour lines spaced at 0.5 mm showing the paths of the spring surface runoff of the water which follows the microstretches in a thin layer. The paths were photographed with the aid of instruments in 1957. The microstretches are so shallow that they are not reflected by the contour lines spaced at 0.5 mm; their depth relative to the surrounding microwatersheds is from 10 to 30 or 40 cm.

By using the method of field soil monoliths isolated on all or only three sides, the following relations of infiltration and consumption for underground drainage in water saturated soils have been established experimentally (N. F. Sozykin, 1940):

	In forest		On pasture-meadow
	on slope 0.15	on slope 0.04	on slope 0.04
Infiltration in isolated monoliths within 30 mins per 1 sq. m., litres	3.6	3.6	4.4
Consumption for underground drainage through non-isolated side wall 1 mm long, litres	27.2	11.1	2.8

From these data it follows $\frac{27.2}{11.1} = \frac{0.15^{0.68}}{0.04^{0.68}}$ that the underground runoff in the forest is close in nature to surface runoff with a small fraction of ground runoff; underground runoff on the pasture-meadow is 5 to 10 times as low as in the forest soil.

With such peculiarities of the runoff mechanism, the following should be taken into account to explain its quantitative differences in and outside the forest:

1. The difference in intensity of snow thawing in combination with infiltration, viz. the difference S—U.

2. The significance of the "regulatory" capacity of the forest soils: this capacity causes the phenomenon of underground runoff in the forest, reduces the maximum moduli of runoff and somewhat lengthens (within one day) the infiltration period.

3. The heat insulating effect of the forest cover abating the cooling and freezing of water in the snow and in the soil at night and in frosts, which

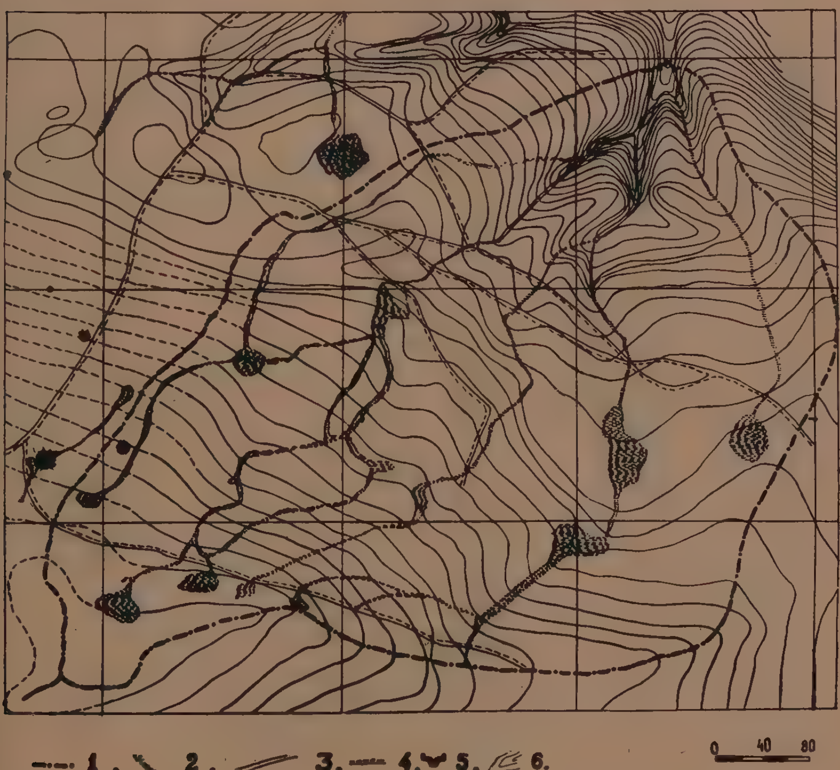

Fig. 1 Plan of spring water paths with contour lines spaced at 0.5 m:
1 - boundaries of forest runoff basin; 2 - paths of water runoff over surface in thin layer; 3 - concentrated streamsbrooks; 4 - roads; 5 - water flow gauge; 6 - contour lines.

leads to the "levelling out" of the runoff in the forest in the course of the day and to a slight increase in the infiltration period.

The combined effect of the above-enumerated factors is vividly manifested in the daily runoff variations in and outside the forest (Table 4, Fig. 2, III).

It can be seen that the daytime consumption in the forest is relatively smaller than that in the field owing to the radiation losses and to the lower intensity of snow thawing under the forest cover, as stated above. The average annual moduli of runoff in the forest for the period from 9 to 18 hours are at all times appreciably below those in the field in spite of the fact that the average slope of the forest basin (0.0015) considerably exceeds that of the field basin (0.0002).

At night, runoff in the forest is relatively higher than outside the forest owing to the regulatory capacity of the forest soils and the heat-insulating effect of the cover. The amplitude of fluctuations in day and night water consumption in the forest is substantially less than that outside the forest.

Fig. 2 combines:

I — graphs of runoff in the forest and field basins in millimeters by days for 1956, 1957 and 1958.

II — Total radiation, cal cm^{-2} day^{-1}, the average daily temperatures $t\,^{\circ}C$, and precipitation, mm, for all days of runoff.

III — The average daily runoff variation in the forest and in the field by hours, per cent of the daily consumption as compared with the average daily variation of total radiation (average values of radiation, cal cm^{-2} min^{-1}, for the whole period of runoff, as observed at 6.30, 9.30, 13.30, 16.30 and 19.30 hrs. local Mean Solar Time).

The figure illustrates the above-mentioned peculiarities of runoff, in the forest (predominantly fir) and outside the forest, on medium-permeability loamy soils, under conditions of temperate climate, with an accumulation of 150-190 mm of water as snow towards spring.

IV. Ratios of runoff factor in and outside the forest

Let us single out the significance of radiation losses, S (found from snow thawing intensity), for the formation of runoff, assuming that the soils of the forest and open basins are equal in water permeability. The probable differences in their moisture content and temperature will be neglected for the present.

Inasmuch as the runoff is caused by the difference S-U, the runoff layer, h, for the period t will be determined from the product τ (S-U). Being unable to establish the true duration of τ as the sum of the momenta of excess of thawing intensity over the infiltration intensity, we make use of the average thawing duration $\tau = \frac{H}{S}$ for approximate calculations, on the basis of the snow reserves, H mm, and the weighted mean thawing intensity, S mm days (taking into consideration the thawing rate in different plantations, on glades and roads, cleared spaces, etc.),

then

$$h_{fo} = \frac{H_{fo}}{\bar{S}_{fo}} (\bar{S}_{fo} - U) \tag{4}$$

$$h_{fi} = \frac{H_{fi}}{\bar{S}_{fi}} (\bar{S}_{fi} - U), \tag{4a}$$

where the subscript "fo" denotes the forest and "fi" the open basin (the field).

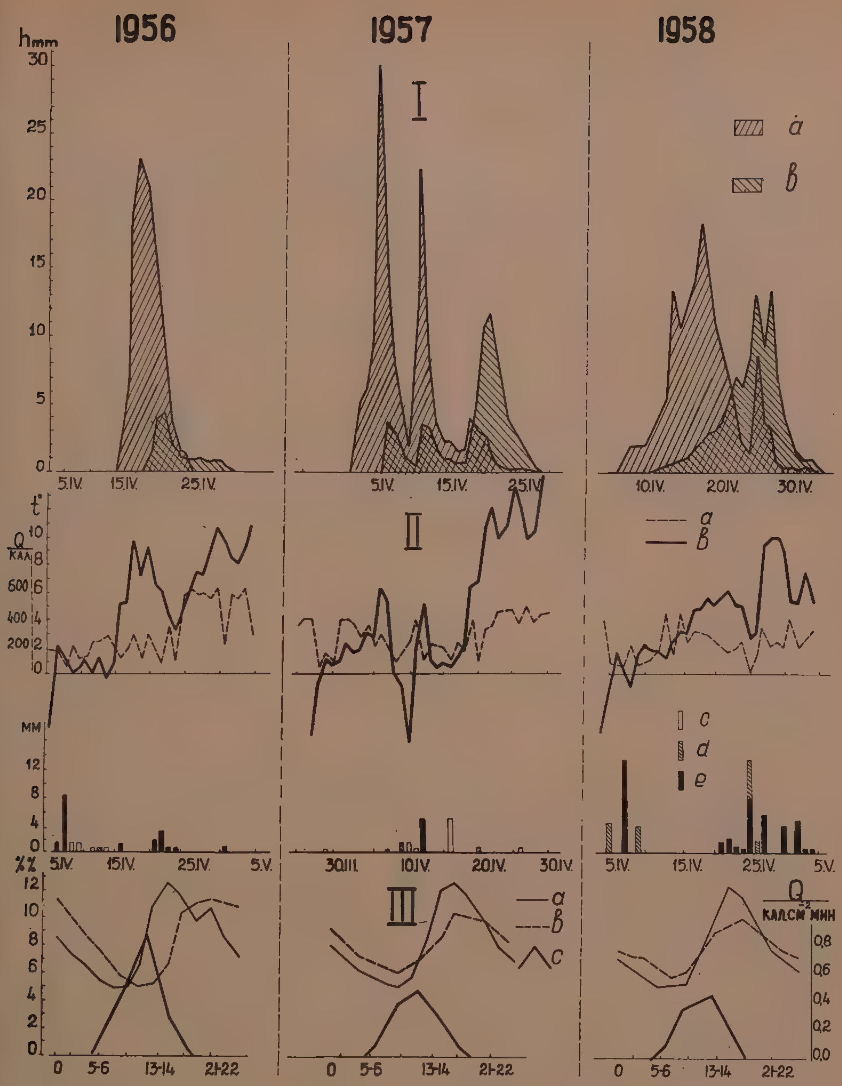

Fig. 2 Peculiarities of spring runoff in and outside forest as observed in 1956, 1957 and 1958.

I. Runoff layer, mm, by days:
   a - outside forest;
   b - in forest.

II. Conditions of thawing and runoff, by days:
   a - total radiation, cal cm^{-2} days^{-1};
   b - average daily air temperature, °C;
   c - snow precipitation, mm;
   d - wet snow precipitation (snow with rain);
   e - rain precipitation (liquid).

III. Runoff volume, by hours (per cent of daily volume), and radiation.
   a - Runoff, ⁰/₀⁰/₀ in field, by hours;
   b - do. in forest, do.
   c - total radiation, by hours, cal cm^{-2}min^{-1}

TABLE IV

Runoff distribution by hours in and outside the forest, $^0/_0{}^0/_0$ of runoff per day

(As observed during the whole runoff period)

Hours	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	Σ % 9-10	Average modulus, 1/sec/ha, during period from 9 to 18 hrs.
Field and meadow														
1956	7.3	6.5	5.4	4.8	4.9	6.6	11.0	12.6	11.7	9.7	10.8	8.7	46.8	1.00
1957	7.4	6.4	5.8	5.3	5.1	5.7	8.5	12.4	12.9	12.0	10.2	8.3	44.6	0.72
1958	6.7	6.0	5.4	5.5	5.7	7.9	11.1	12.9	12.3	10.4	8.5	7.6	49.9	0.73
Forest														
1956	10.2	9.0	7.9	6.4	5.4	4.9	5.3	6.5	10.4	11.2	11.5	11.3	32.5	0.12
1957	8.4	7.5	7.0	6.5	6.3	6.7	7.9	8.8	10.7	10.4	10.3	9.5	40.4	0.31
1958*)	7.7	7.6	6.9	6.2	6.6	7.9	9.4	10.3	10.5	9.7	9.0	8.2	44.7	0.26*)

*) Since the amount of liquid precipitation on 26. IV. was 13.6 mm, the daily variation and the runoff modulus in the forest are calculated only for the period from 7. IV. to 22. IV.

From Eqs. (4, 4a) we find the ratio of spring runoff in the forest and in the field, K_{fo} and K_{fi}

$$\frac{K_{fo}}{K_{fi}} = \frac{(\bar{S}_{fo} - U)\, S_{fi}}{(\bar{S}_{fi} - U)\, S_{fo}} \tag{5}$$

Hence,

When filtration is low and the differences $\bar{S}_{fo}$-U and $\bar{S}_{fi}$-U are close to $\bar{S}_{fo}$ and $\bar{S}_{fi}$, respectively (on semi-permeable soils or in the presence of ice), the runoff factors in the forest and in the field are rather similar. So, the factor of the lower intensity of snow thawing in the forest loses its significance.

In the case of high infiltration, when $U = \bar{S}$ or $U > \bar{S}$ (for instance, on sandy soils) runoff is hardly probable, therefore the difference between $\bar{S}_{fo}$ and $\bar{S}_{fi}$ also lose their significance.

For the purpose of this paper it is permissible to replace the differences $\bar{S}$-U in Eq. (5) by the average runoff moduli M_{fo}, M_{fi} for the day hours from 9 to 18 hrs. when the thawing intensity vs. radiation intensity is of decisive importance, and the quantitative difference between runoff in the forest and that in the field is most pronounced.

Basing our calculations on this fact, we find them from Tables 1 and 4

$$\frac{K_{fo}}{K_{fi}} = f\,(S, U)$$

for 1956

$$\frac{K_{fo}}{K_{fi}} = \frac{M_{fo} S_{fi}}{M_{fi} S_{fo}} = \frac{0.12 \times 9.8}{1.0 \times 5.9} = 0.2, \text{ actually } \frac{K_{fo}}{K_{fi}} = \frac{0.1}{0.56} = 0.18$$

for 1957:

$$\frac{K_{fo}}{K_{fi}} = \frac{0.31 \times 11.0}{0.72 \times 5.5} = 0.86, \text{ actually } \frac{K_{fo}}{K_{fi}} = \frac{0.46}{0.88} = 0.52$$

for 7. IV—22/IV, 1958:

$$\frac{K_{fo}}{K_{fi}} = \frac{0.26 \times 11.3}{0.73 \times 5.3} = 0.76, \text{ actually } \frac{0.22}{0.62} = 0.35$$

Under the conditions of the spring of 1956 when the thawing was rapid (without frosts) the estimated ratio $\frac{K_{fo}}{K_{fi}} = f\,(S,U)$ coincided with the actual evidence, consequently the radiation losses and the difference in the thawing intensities were the decisive cause for the quantitative difference in the drainage.

The estimated ratios $\frac{K_{fo}}{K_{fi}}$ for 1957 and 1958 differ from the actual data. These differences can be due only to the fact that the significance of the regulatory capacity of the forest soils and the heat insulating effect of the cover in the period from 18 to 9 hours made itself felt in those years meaning that the difference in moisture content the temperature and the state of the soils are reflected in the values of the moduli M_{fo} and M_{fi}.

We denote this additional effect (of the soil capacity and the heat insulation) by the symbol $\triangle$ and determine it from the equation

$$\frac{K_{fo} \text{ act.}}{K_{fi} \text{ act.}} = \frac{M_{fo}\, \bar{S}_{fi}}{M_{fi}\, \bar{S}_{fo}} \tag{6}$$

For 1956 $\triangle = 0.9$, for 1957 $\triangle = 0.60$, for 1958, in the first phase of thawing and runoff $\triangle = 0.46$.

It should be noted that $\triangle$ in Eq. (6) is, as it were, a "decrease coefficient" for the moduli runoff in the forest, maximum moduli in particular.

V. Conclusion

It may be considered an established fact that the daytime decrease in the intensity of snow thawing under the plantation cover (owing to the losses of short-wave radiation in the forest cover and the insufficient supply of long-wave radiation), decreases the runoff factor in the forest on medium-permeability soils 1.2 to 5 times as against the runoff factor in the open basin. The regulatory capacity of medium-podsol loamy soils under the fir forests and the additional heat-insulating effect of the forest cover under certain night-time thermal conditions reduce the runoff factor by another 1.7 to 2.0 times.

Observation data for 10 years (Fig. 3) reveal that the spring runoff factor in a 90 % forest basin with prevalence of firs is, on the average, close to 0.3, whereas in an open basin (with 13 % forest coverage) it equals 0.7 which essentially confirms the relations found.

The annual runoff factors are, of course, a function of humidity, soil freezing and ice formation, but there can be no doubt that each year the forest contributes to the reduction in the snow thawing intensity and the runoff volumes because of radiation losses. Of some importance is also the effect of the physical conditions of the forest diminishing the maximum moduli of spring drainage (Fig. 3) which follows from Eq. (6). This is well known to serve as the basis for using the forest in soil erosion control.

The presented data, hypothesis and calculation patterns are important for a more detailed elaboration of programs for forest hydrological observations and further investigation of the hydrological effect of forests (significance of the forest coverage percentage, configuration and the size of forest meassives and patches, their composition and location in the basins) on the background of various geological, geomorphological and climatic conditions.

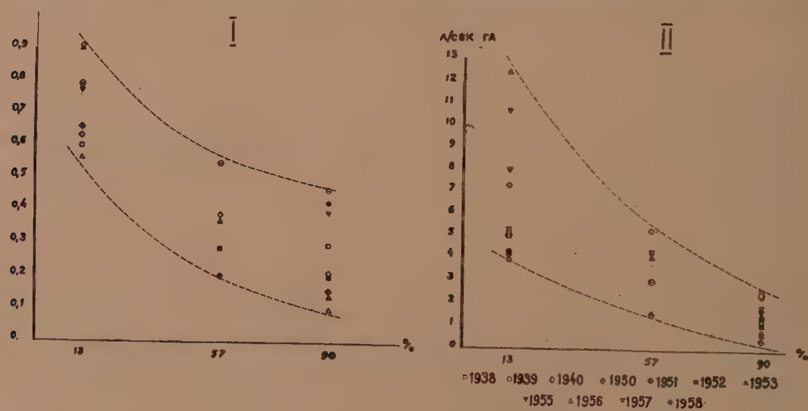

Fig. 3 Coefficients (I) and maximum moduli (II) of the runoff, 1 $sec^{-1}ha^{-1}$, by years, as function of the forest coverage of runoff basins, %%.

SUBSOIL WATER OF KAMENNAYA STEPPE AND THE INFLUENCE OF FOREST STRIPS UPON ITS REGIMEN

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SUMMARY

In 1891, the Central Black Earth regions suffered a severe drought. To study the cause of droughts and to work out measures for combating them, an expedition was organized in 1892. The expedition chose the Kamennaya steppe as one of the experimental areas to combat drought. In 1892-1894 the first field protecting forest belts were planted and afforestation was carried out near gullies, ponds, etc.

The following conclusions should be drawn from the presented study:

1. Under the influence of forest strips, the range of sub-soil water level fluctuations increases yearly, which is due to the accumulation of a mass of snow in the forest strips. The redistribution of the surface runoff and the improvement of the microclimate.
2. The forest strips contribute to an improved uniform distribution of the mass of snow in the fields between the strips, increasing the humidity of the soil.
3. As viewed from a long-term aspect, there is no progressing rise or drop in the level of the subterrenean water

RÉSUMÉ

En 1891, la région centrale des Terres Noires fut affectée par une sévère sécheresse. Pour étudier les causes des sécheresses et pour y remédier, une expédition fut organisée en 1892 qui choisit la steppe de Kamennaya comme surface expérimentale dans la lutte contre la sécheresse. En 1894, des zones forestières de protection furent plantées. L'étude actuelle présente les conclusions auxquelles l'étude des résultats a conduit :

1. Sous l'influence des zones forestières, l'amplitude des fluctuations de la nappe a augmenté annuellement, ce qui est dû à l'accumulation d'une masse de neige dans les parties couvertes de forêts, à la redistribution de l'écoulement de surface et à l'amélioration du microclimat.
2. D'autre part, l'implantation des zones forestières a conduit à une distribution améliorée des masses de neige dans les espaces ouverts entre les bois, augmentant l'humidité du sol.
3. Une étude à long terme ne montre aucune montée ou baisse du niveau de la nappe.

The Kamennaya Steppe is situated in the Talov district of the Voronesh region in the European part of the Soviet Union. It represents an area where fields alternate with forest strips of various ages. At present the area is a classical example of transformation of nature by man.

In 1891, the Central Black Earth regions suffered a severe drought which caused devastating damage to Russia's agriculture and attracted the attention of many scientists.

To study the causes of droughts and to work out measures for combating them, an expedition of the Forest Department was organized in 1892, headed by V. V. Dokuchayev, a distinguished Russian scientist.

By that time Russia had already gained sufficient experience in setting up field-protecting forest belts in the south of the Ukraine and in the Central Black Earth regions.

In summing up the experience in field-protecting afforestation, the Dokuchayev expedition established that by changing the microclimate of agricultural fields, the field-protecting forest strips improve the growth of agricultural crops, contribute to a more uniform distribution of snow and increase humidity in the fields.

The expedition chose the Kamennaya Steppe as one of the experimental areas to combat drought, and planted the first protective forest belts in 1892-1894. It dug a well in area No. 69 to observe the level of subsoil water. This marked the beginning of a study of the subsoil water conditions as influenced by the forest strips of the Kamennaya Steppe, which has continued to this date.

In the following years, since 1894, field-protecting forest belts were planted and afforestation was carried out near gullies, ponds, etc., according to a plan elaborated by V. V. Dokuchayev. At the same time ponds were dug, gullies were kept from erosion by afforestation, and other work was carried out.

In setting up forest strips in the Kamennaya Steppe it was meant to study the best methods of distributing the strips in the area, and their importance in combating the mechanical effects of winds and for snow retention as live fences, moisture-collecting plantings, etc.

The main wind-protecting strips run from north to south taking advantage of the peculiarities of the terrain, with due consideration for the direction of the most harmful eastern winds. Auxiliary forest strips run in a latitudinal direction, perpendicular to the main strips. The Kamennaya Steppe is divided by the forest strips into field rectangles and squares. In the highest watershed parts of the area, the main wind-protecting strips are as wide as 110 m. The auxiliary shelter belts are from 6.5 to 30 metres wide. The inter-strip squares, limited by the shelter belts of the early plantings, cover an area ranging from 8 to 25 hectares. In the following years, as a result of the rapid progress in agricultural techniques, the inter-strip glades were made as large as 30 to 60 or even 100 hectares.

The composition of the plantings varies greatly and comprises the following species listed in the decreasing order by the percentage of the plantings: oak, maple, ash-tree, birch, elm, and scattered pear and apple trees. At present the trees of the early plantings have reached a height of 20 m. In almost every forest strip there is an undergrowth consisting of yellow acacia, Tartar maple, European spindle tree, honeysuckle, birdcherry trees and other species. As a rule, the forest has a dense edge consisting of elm, Tartar maple, hawthorn, yellow acacia, lilac and sweetbrier.

The Kamennaya Steppe has a continental climate. The average temperature of the air, according to observations for many years, ranges from 4.9 to 5.8 °C, and precipitation amounts to 392 mm per year. The annual absolute humidity of the air averages 7.5 mb for the steppe areas, and 8.1 mb for the afforested sections. The average annual wind velocity amounts to 5 m/sec for the open steppe spaces, while in the fields among the forest plantings it diminishes by 20 to 30 per cent since the forest strips serve as good windbreakers. According to observations for many years, evaporation from the surface of the soil amounts to 374 mm a year, and from the surface of the water to 750 mm. According to the same data, the runoff from the surface of the soil averages 94 mm.

The geological structure of the Kamennaya Steppe comprises rocks of the Devonian, Cretaceaus, Tertiary and Quarternary periods.

The Devonian deposits were found at a depth of about 143 m; they represent a mass of variegated clay and limestone of the Schigrov horizon having a depth of 50 m. The Devonian rocks are overburdened by deposits of the Cretaceous period represented by fine—and medium-grained sand of the Senoman and Albian stages, turning into cretaceous rocks of the Turonian-Cognac stages. The total thickness of the cretaceous deposits in the Kamennaya Steppe does not exceed 100 m.

Of Tertiary deposits, Paleogenes are encountered in the Kamennaya Steppe, represented by fine-grained sand and glauconite sandstone of the Buchak stage up to 18 m thick and greenish-gray clay of the Kharkov stage up to 12 m thick.

The mother rocks are overlain with a thick cover representing an intricate complex of Quarternary deposits. The complex consists of a moraine of the maximum Dnieper-Don glaciation (boulder loam with sparse sand lenses) up to 30 m thick, lake-alluvial ("Odintsovo") loam up to 10 m thick, and eolian-deluvial blanket loam deposit from 3 to 4 m thick. Apart from this, alluvial deposits can be traced in the gullies.

The subsoil water in the Kamennaya Steppe, whose conditions are due to the influence of the forest strips and are studied by the Hydrogeological Station, belongs to the same period as the Quarternary deposits. The water-holding rock consists of "Odintsovo" loam and eolian-deluvian loam. The entire mass of loam has a complicated system of cracks and cleavages and is characterized by microporosity. All this accounts for its permeability.

The thickness of the water-bearing horizon of the Quarternary deposits does not exceed 10 m. Subsoil water is encountered at a depth of 1 to 3 m in the gullies and 8 to 14 m in the watersheds. The moraine provides a water-resistant layer for this horizon. Generally, the watershed of subsoil water coincides with that on the surface of the area. Subsoil water runs from the watershed in various directions, in line with the lowering of the terrain, the incline of the water table ranging from 0.022 to 0.004.

Drainage of the water-bearing horizon of the Quarternary deposits is effected, in the main, via scanty shallow sources outside the area, and in the Kamennaya Steppe as such, through evaporation and transpiration by the vegetation.

The temperature of subsoil water changes during the year from 1.5 to 12 ° C, depending on the depth of the water-bearing horizon and the rate of infiltration of thawing snow in spring.

Mineralization of the Kamennaya Steppe subsoil water varies from 300 to 4700 mg/l.

The investigations conducted in the Kamennaya Steppe and analysis of the data thus obtained have revealed regularities in the yearly and long-term fluctuations of subsoil water level.

The conditions of subsoil water during the year are chiefly determined by climatic factors among which precipitation is of major importance in feeding subsoil water, and evaporation and transpiration in its loss. There is no inflow of subsoil water from the neighbouring areas, as the Kamennaya Steppe is situated on a watershed.

The yearly conditions of the Kamennaya Steppe subsoil water is greatly influenced by the forest strips of different ages, which accumulate considerable quantities of snow in winter, thereby creating conditions for subsoil water under the forest strips and on the glades between the strips, differing from those in the areas outside the zone influenced by the forest strips. The

accumulation of snow in winter creates favourable conditions for feeding the water-bearing horizon in spring. The amount of water and the rate of its inflow to the water-bearing horizon due to thawing snow depends on the age and size of the given forest strip, its location in the terrain, the depth of the water-bearing horizon, and the relief.

In summer and partly in autumn, the forest strips consume considerable quantities of moisture for transpiration, which causes the level of the water-bearing horizon to shift down.

During the year, the level of subsoil water does not remain stable, changing within 1 to 3.5 m. Between January and March, the level of Kamennaya Steppe subsoil water fluctuates slightly, an insignificant rise being usually recorded during the period. In some years there is a thaw during these months, which results in slight rises in the level, chiefly in shallow wells (down to 5 m) of subsoil water. From the end of March, the level of subsoil water rises, depending on the beginning of the spring high water, and reaches its maximum position in April or May, and sometimes in June or even in July. When the level has reached its maximum position, it begins to drop, and the minimum occurs in September and October. Slight fluctuations of the level continue in November and December or it rises slowly.

The nature of the subsoil water level fluctuations depends on the age of the given forest strip, the location of the observation point, accumulation of snow, the lithologic composition of the aeration zone, and the depth of the water-bearing horizon. This is vividly illustrated in Fig. 1 and Table 1, which present by way of example the charts of subsoil water level fluctua-

TABLE I

Location of observation points	Average yearly depth of sub-soil water, metres	Reserves of snow water, mm	Average height of spring rise in level, metres	Average drop in the level, metres
Forest strips aged from 50 to 65 years, and their edges.	4.70	119	2.46	3.02
Ditto	6.03	119	1.41	1.51
Forest strips aged from 6 to 20 years, and their edges.	3.09	216	3.06	3.28
Ditto	5.57	124	1.17	1.59
Glades among the forest strips	3.69	42	0.72	1.54
Ditto	5.11	64	1.52	0.90
Steppe	8.10	53	0.62	0.10

Note: The above figures are average for all the wells.

tions for 1957 by the wells situated under various conditions with relation to the forest strips. Thus, according to the data obtained from observation points located in forest strips aged from 50 to 65 years, at the water-bearing horizon depth of 1-4 m, the curve of level fluctuation shows a rapid rise in two to four weeks and a relatively smooth drop. In similar forest strips, at the water-bearing horizon depth of 4-6 m, a smooth rise has been recorded for two months, followed by a smooth drop.

In forest aged from 6 to 20 years, at the water-bearing horizon depth of 0-5 m, a rapid rise in the level is observed during a month, followed by a drop, at first drastic and then smooth.

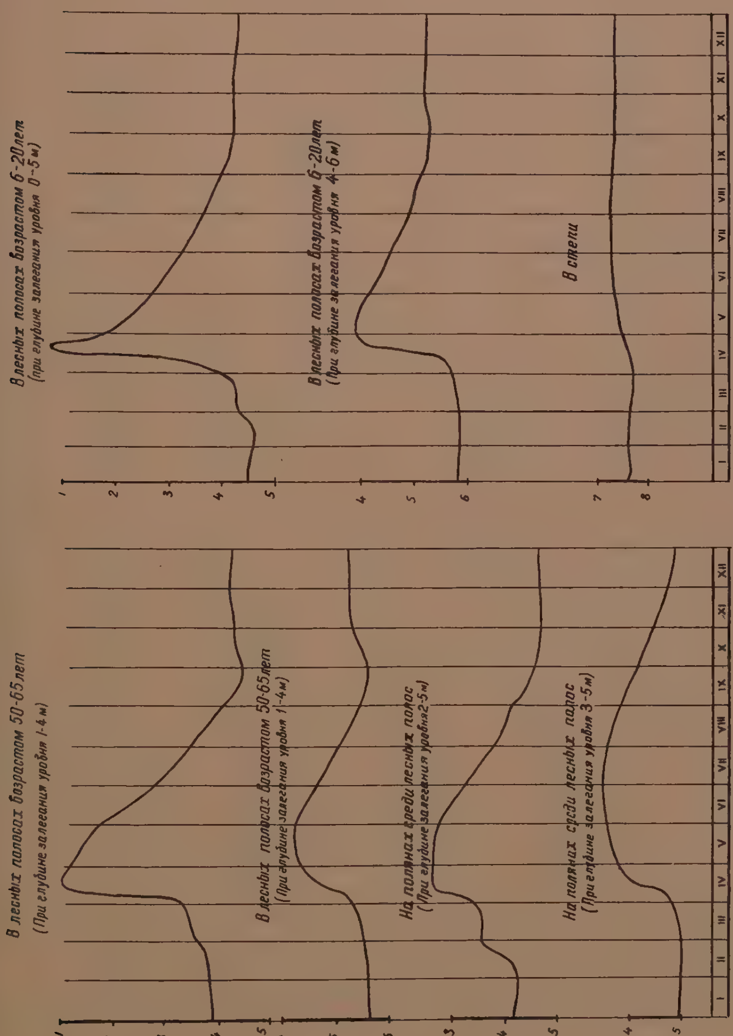

Рис. 1.

Графики колебания уровня грунтовых вод по скважинам, расположенным в различных условиях по отношению к лесным полосам

In forest strips of the same age but with the depth of the water of 4-6 metres, a rather rapid rise in the level and a stable maximum during a month, followed by a smooth drop is observed.

In wells located on glades among the forest strips, the rise in the level of the water-bearing horizon is comparatively smooth, and the stable maximum continues for six weeks to four months, followed, as a rule, by a smooth drop up to the end of the year.

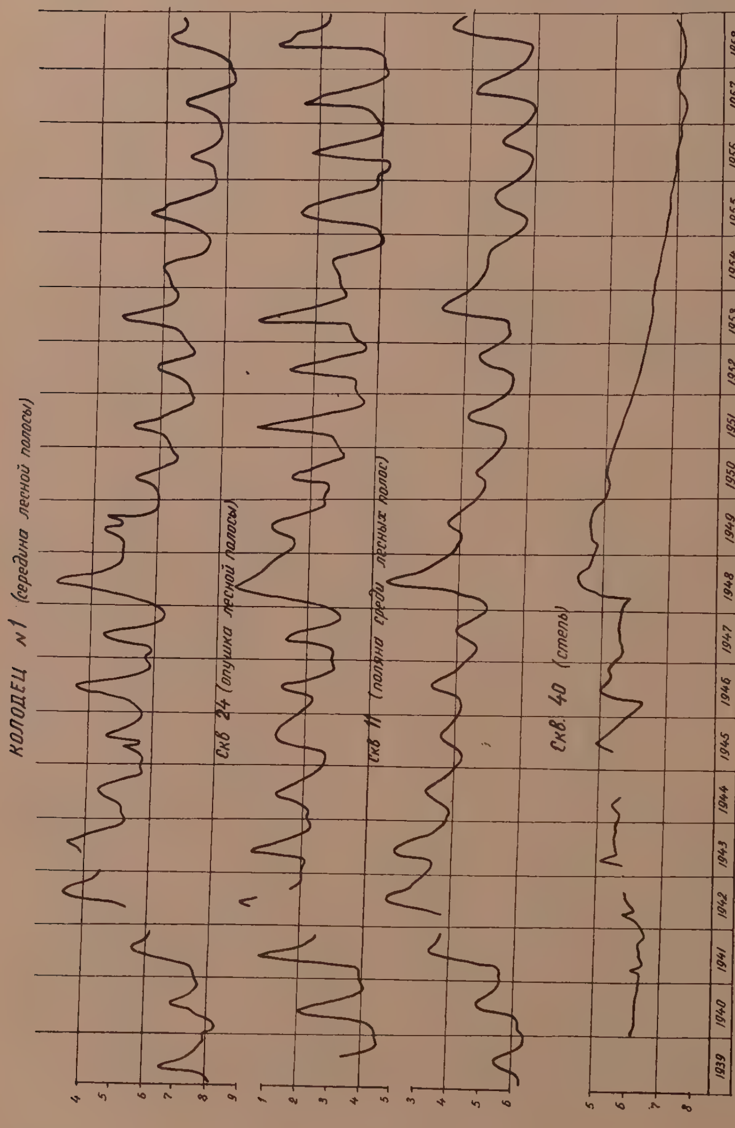

РИС 2

Кривая колебания уровня грунтовых вод по скважинам, расположенным в различных условиях по отношению к лесным полосам

In wells located in the steppe, the rise in the level of subsoil water due to spring high water, is manifested slightly. During the year, the level fluctuates insignificantly.

The nature of fluctuation of the subsoil water level in wells located under various conditions with relation to the forest strips is generally constant from year to year. This can be clearly seen from analysis of Fig. 2, giving typical curves of Kamennaya Steppe subsoil fluctuations in wells located under various conditions with relation to the forest strips. The curves have been plotted by the average monthly positions of the level. The nature of the curves of level fluctuation in the wells located in the forest strips, on their edges and on the glades among the forest strips is qualitatively quite the same. In each of the three cases the position of the level has common regularities within the year. Spring high water brings about a rise in the level of subsoil water, and the maximum and minimum positions coincide in all the three cases.

There are no pronounced rises, followed by drops, in the level in the wells located in the steppe during spring high water.

Data for many years indicate that there is either a general rise or a drop in the level, along with annual fluctuations. Such fluctuations are qualitatively common for all wells in the Kamennaya Steppe. Thus, between 1939 and 1942, there was a gradual rise in the level, followed by a drop. Then, in 1948, a rise sets in, followed by a prolonged general drop, lasting till 1957.

As pointed out above, the qualitative aspect of the changes in the level for many years is quite similar for all wells of the Kamennaya Steppe, located under different conditions with relation to the forest strips.

The level of subsoil water in the steppe areas undergoes slight annual and long-term fluctuations. This is largely accounted for by the fact that in the unsheltered areas the snow is blown off in winter, and during high water the snow water provides little replenishment for subsoil water reserves.

The edges and forest strips show strongly pronounced fluctuations of the subsoil water level during the year and over a period of many years.

In the central part of the forest strips, about 100 or more metres wide, there no influence of any particular factor is manifested. The snow from the surrounding fields does not drift there, since it is retained at the edges of the forest, nor is it blown away from such strips. The level of subsoil water in the centre of such forest strips or tracts changes under the impact of a complex of meteorological elements, and not as a result of any predominant factor. Therefore well No. 1 located in the centre of a wide forest strip, is used to define the long-term fluctuations of the subsoil water level. Observations of its water level have been conducted since 1892; hence, they are of considerable interest. Fig. 3 shows the long-term position of the subsoil water level in the well, as recorded on September 1 of every year.

Analysis of the curve of the subsoil water level fluctuations in well No. 1 for the period 1892-1958 demonstrates a well pronounced rhythm in the fluctuations. Periods of high subsoil water level are followed by a period with a low level, in other words, viewed from a long-term aspect, the level does not remain stable, but undergoes fluctuations. The minimum positions of the subsoil water level were recorded in 1892, 1900-1904, 1914, 1925, 1939 and 1957, all in all six times. The level attained its maximum in 1897, 1907, 1919, 1929 and 1942, i.e. five times. The last two maxima are spread out and produce two well pronounced peaks: in the first case, 1929 and 1933, and in the second case, 1942 and 1948.

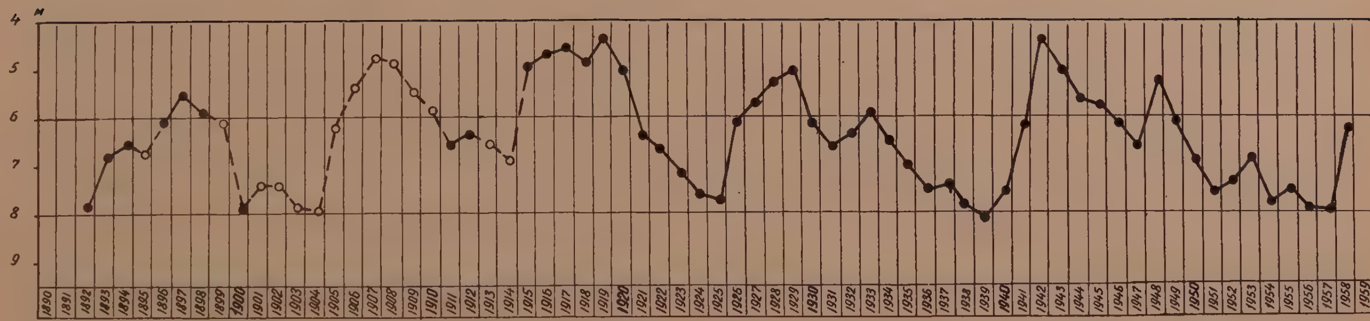

РИС 3

Кривая колебания уровня грунтовых вод по колодцу № 1, расположенному в лесной полосе № 69 Каменной Степи

(Уровни даны в глубинах от поверхности земли на 1 сентября каждого года)

Примечание: *Положение уровня грунтовых вод за период с 1899 по 1915 взято автором из работ проф. Г. Ф. Басова. За этот период уровни им вычислены по корреляционным зависимостям и обозначены ○.*

● *Положение уровня по фактическим данным.*

TABLE II

Year		Duration, years		Magnitude, metres	
Maximum	Minimum	Rise	Drop	Rise	Drop
1892	1897	5	—	2.30	—
1900	—	—	—	—	2.46
—	1919	—	6	—	3.53
1925	1929	4	10	3.64	3.87
1939	1942	3	15	3.73	3.56
1957	—	—	—	—	—

Thus, beginning with the lowest level, i. e. since 1892, and ending likewise with the lowest subsoil water level in 1957, there were five complete rhythms in the fluctuations of the Kamennaya Steppe subsoil water during the 65 years. The average duration of the rhythm during the period amounted to 13 years, i. e. its duration is close to the eleven-years cycle of the manifestation of solar activity.

Table 2 presents data on the duration, rise and lowering of the subsoil water level in well No. 1 according to actual measurements.

As seen from the Table, the rise in the level increased from 2.30 m to 3.73 m between 1892 and 1942. Between 1919 and 1957 the drop in the level likewise increased, namely from 2.46 m to 3.56 m.

It should be noted that the duration of the drop in the subsoil water level in well No. 1 generally tends to increase. For example, between 1919 and 1925 the level dropped during 6 years, between 1929 and 1939 during 10 years, and between 1942 and 1957 during 15 years.

Analysis of the maximum and minimum levels will provide an answer to the question whether there is a progressing long-term rise or drop in the subsoil water level under the influence of the forest strips in the Kamennaya Steppe. In comparing the maximum levels, the 1919 and 1942 data are used, and at the minimum level the 1925 data are compared with those of other years. The year of 1925 is taken as a basis for comparison since it is the first well pronounced minimum based on actual data. The year of 1892 likewise witnessed a minimum subsoil water level, but that year is used for comparison only, and not as a basis, since the minimum has not been confirmed by previous actual measurements.

The minimum of the subsoil water level in the Kamennaya Steppe for 1892-1957 is given in Table 3.

In comparing the minimum subsoil water level in well No. 1 for 1957 with the actual measurements of 1925 and 1892, we obtain a difference pointing to a lowering of the level by no more than 0.06—0.10 m. It goes without saying that such a negligible drop in the level for such a long period of observations does not justify any assumption to the effect that there is a progressing lowering in the level of subsoil water under the influence of the Kamennaya Steppe forest strips.

TABLE III

Years of minimum of the subsoil water levels, as of September 1	Depth of subsoil water level, in metres, from the surface of the ground, as of September 1	Difference in metres + rise — drop
1925	7.84	— 0.23
1939	8.07	
1925	7.84	
1957	7.90	— 0.06
1892	7.80	
1900	7.96	— 0.16
1892	7.80	
1925	7.84	— 0,04
1892	7.80	
1939	8.07	— 0.27
1892	7.80	
1957	7.90	— 0.10

The year of 1939 witnessed the lowest level for the whole period of observations. That year evidently marked the end of subsoil water fluctuation rhythm of a greater duration than noted above, and, consequently, a comparison of 1939 with other years is made with some caution.

As the duration of observations of Kamennaya Steppe subsoil water level increases, it will be possible to reveal a rhythm of level fluctuations of a much greater duration than 10 to 13 years.

From comparison of the maximum position of the subsoil water level of 1919, amounting to 4.31 m from the surface of the ground, with that of 1942, amounting to 4.34 m, it can be seen that the level of subsoil water does not rise under the influence of the forest strips.

A comparison of both the minimum and maximum positions of the level infers that, viewed from a long-term aspect, the level does not tend either to rise or drop progressively under the influence of the forest strips. As can be seen from analysis of Fig. 3 and the data given above, the long-term level of the Kamennaya Steppe subsoil water undergoes rhythmical fluctuations. The rhythm of the level fluctuations is caused by general climatic factors and the manifestation of solar activity.

The following conclusions should be drawn from the above:

1. Under the influence of the Kamennaya Steppe forest strips the range of subsoil water level fluctuations increases yearly, which is due to the accumulation of a mass of snow in the forest strips, the redistribution of the surface runoff, and the improvement of the microclimate.

2. The forest strips contribute to an improved uniform distribution of the mass of snow in the fields between the strips, increasing the humidity of the soil and thereby creating better conditions for the growth of agricultural crops.

3. As viewed from a long-term aspect, there is no progressing rise or drop in the level of subsoil water under the forest strips in Kamennaya Steppe, but the level undergoes rhythmical fluctuations which are qualitatively similar for afforested and non-afforested areas (glades, steppe). The fluctuations are brought about by changes in the solar activity which predetermines changes in the climatic conditions. In the final analysis, the Kamennaya Steppe forest strips cannot, therefore, cause undesirable phenomena of bogging up or drying off of the territory. On the whole the forest strips play a great favourable role in improving the general water balance of the territory.

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THE EFFECTS OF TIMBER PLANTATIONS ON WATER SUPPLIES IN SOUTH AFRICA

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SUMMARY

This paper describes the development of the "forests and water" problem in South Africa, from the end of the 19th century, when the forest was looked upon as a panacea in water catchment management, to the present day, and attempts to place the problem in its proper perspective in the light of current knowledge. Recommendations are made in regard to the use of forestry in catchment management to achieve flood-control and efficient water yield utilization.

RÉSUMÉ

Cet article décrit le développement du problème « Forêts et Eau » en Afrique du Sud, depuis la fin du 19e siècle, quand la forêt était considérée comme la panacée pour l'aménagement des captages d'eau, jusqu'au jour présent, et essaye de placer le problème à sa vraie place à la lumière des connaissances courantes.

Des recommandations son faites en ce qui concerne l'utilisation de la forêt dans l'aménagement des captages pour réaliser le contrôle des crues et une utilisation efficiente de la réserve d'eau.

Introduction

The climate of South Africa is generally too arid for forestry. From the Namib desert along the west coast, where the annual rainfall is less than 10 mm., towards the eastern Cape Province, Orange Free State and Transvaal the rainfall increases to 800 mm. per annum. On the precipitous mountains of the South-western Cape Province, the Amatola mountains to the east, along the east coast from the Kei river to north of St. Lucia Bay, in the Natal Midlands, along the Drakensberg and the escarpment of the eastern Transvaal to the Soutpansberg in the north, climatic regions meriting commercial forestry are found. These receive an annual rainfall of 800 to 1,000 mm. and more. But, only a small fraction of these high-rainfall regions are ecologically suitable and available for forestry.

All important South African rivers, however, rise in these parts, and the appropriate management of the upper catchments to preserve and improve the water supplies of the country is imperative in order to ensure the future of industrial and municipal development and irrigation schemes.

The natural hardwood forests of South Africa occur in small relatively unimportant remnants, but afforestation with exotic tree species is being rapidly expanded. Various species of *Pinus*, *Eucalyptus*, *Acacia* and *Populus* are planted. The total area of plantations of exotics in 1955 was about 813,000 hectare. It is estimated that this area will be extended by about 70 per cent to about 1,382,000 hectare, and that the limit of afforestation will be reached in about the year 2,000 or shortly afterwards.

Optional forms of catchment management in these parts include: total protection of natural grass, shrub and forest vegetation; veld-burning;

mowing; bush removal by slashing or poisoning; cultivation and pasturage. The hydrological effects of afforestation with exotics is being experimentally compared with various forms and combinations of these treatments at five centres, viz., the Jonkershoek, Cathedral Peak and Mokobulaan Research Stations of the Government Forestry Department, the Deepdene Research Station of the Natal Tanning Extract Company and Westfalia Estate of the Merensky Trust. These are situated in the Cape mountains near Stellenbosch, on the foothills east of the Drakensberg near Winterton, Natal, on the escarpment near Nelspruit, Transvaal, in the Natal Midlands near Richmond and on the escarpment near Tzaneen, Transvaal, respectively.

This paper presents the latest conclusions on the effects of plantations of exotic timber trees on water supplies in South Africa.

The Forest and Water Controversy in South Africa.

The essential relationship between forests and water in South Africa was stressed by Dr. John Croumbie Brown in his reports as Government Botanist at the Cape from 1863 to 1867 and in his books published in 1875 and 1877. Brown attributed the aridity of South Africa largely to the paucity of forests, and, after an exhaustive study of the literature available at that time, including the works of Marsh (1874), Surell (1841) and Ebermayer (1873) he came to the following general conclusion: "The effects of forests in retarding the flow of the rainfall after its precipitation has been established, I consider, beyond all question; and not less so their effect in maintaining a general humidity of atmosphere and soil." He rated the beneficial hydrological effects of forests too high, particularly in regard to their effect on rainfall, and did not sufficiently take into account the high vapour-losses which occur in South Africa when applying conclusions drawn in cooler regions in the northern hemisphere to local conditions, but no local data existed then, and so his conclusions were justifiable at the time. He rendered a valuable service by stimulating thought on this vital subject at an early date.

Dr. H. G. Fourcade in his able "Report on the Natal Forests" (1889) gives a lucid account of the influences of forests on water supplies. He deals separately with the influence on rainfall, the rainfall-interception by forest canopies, the infiltration and absorption of moisture by forest soils, the retardation of surface run-off and the control of torrents and floods. His conclusions, which were more conservative than those of Brown, were based largely on the information compiled by Brown. The following quotations from Fourcade's report provide a résumé of his conclusions:

"... if forests do not materially augment the rainfall, they unquestionably regulate it, promote the frequency of showers and control the flow of water, which, on the whole, is a preferable effect." "... when rain falls over a forest (a) the rain itself, though more frequent, is less intense; (b) a large proportion of the water, averaging fully one quarter of the total amount is retained by the tree-tops with their vast expanse of foliage, and restored to the atmosphere by evaporation; the trunks and the undergrowth help to retain some of the water. (c) When the rain at length reaches the ground, the saturated vegetation serves still to break the shock of heavy showers, and to keep the water dispersed over the surface, where it is imbibed slowly by the spongy humus which is capable of absorbing an immense quantity." "In this manner, the forests store immediately by far the greater part of the rainfall, and yield it little by little, trickling in water of perfect fluidity, instead of forming swollen streams charged with mud and gravel." "If forests lose little moisture by direct evaporation from the soil, they exhale through foliage an immense quantity of vapour into the atmosphere."

In general, Fourcade's report reflected the consensus of opinion held at the end of the 19th century, which was also more fully set forth in bulletin No. 7 of the United States Department of Agriculture (1893) on "Forest Influences." Similar ideas were expanded by Braine in a paper read before the South African Association for the Advancement of Science in 1908.

The establishment of plantations of exotic timber trees began towards the end of the 19th century in South Africa. Since then extensive "man-made forests" have replaced natural vegetation in areas which had been covered with grass or shrub for many years, usually for centuries. The forest and water problem in South Africa has, therefore, not developed because of the destruction of natural coniferous and deciduous forests as in Europe and North America, but because of the establishment of artificial forests where there were none before. Here, as in the northern hemisphere, the beneficial effects of indigenous forests were never doubted. Their destruction has always been deprecated; their protection commended. During the past sixty years doubts as to the favourable effects of plantations of exotics on water supplies have, however, been repeatedly expressed. It has been alleged that plantations dry up water supplies, exhaust the soil and promote erosion. These rather extravagant claims were based on casual observations, without the assurance that the results observed were independent of uncontrolled extraneous influences. The foresters, who insisted that such plantations should be extended, emphasised their economic utility, but could not adduce reliable evidence that desirable indirect benefits would derive from them. The actual influence of afforestation in South Africa on the water cycle has not yet been fully observed and explained.

At the time of the Empire Forestry Conference held in South Africa in 1935 the attack on the Government afforestation policy had become so serious that the Minister of Agriculture and Forestry requested that a committee should be appointed to report on the effects of forests on climate, water conservation and erosion with special reference to South Africa. In the committee's report, as approved by the Conference and submitted to the South African Government, it was suggested that "a comprehensive scientific investigation on the effects of treeplanting upon local water supplies would be of value not only to South Africa, but also to other parts of the Empire." (Forests etc., 1935).

The Government responded immediately and the Jonkershoek Research Station was established in the same year. In 1936 the Cathedral Peak Research Station was selected, but development was suspended during the war and restarted in 1945. In 1955 the Mokobulaan Research Station was established. The private Research Station of the Natal Tanning Extract Company at Deepdene was started in 1953 and the establishment of the private station on the Westfalia Estate of the Merensky Trust is proceeding (Wicht, 1948; Beard, 1955; Nänni, 1956; Wicht & Schumann, 1957; Wicht, 1959(a)).

The final solution of the problem of the effects of tree-planting on water supplies in South Africa will depend on the outcome of investigations at these research centres.

The forests and water controversy continued unabated after 1935, and this led to the preparation of a report in 1949 in which it was attempted "to synthesize the meagre and sometimes problematic data available into a coherent statement" with the object of placing the problem in its proper perspective (Wicht, 1949). Very few scientific publications presenting data derived from research or conclusions drawn from logical theoretical analyses

of the problem appeared before 1949 (Beekhuis, 1943; Gevers, 1948; Henrici, 1943 & 1946; Keet, 1940; Rycroft, 1947; Wicht, 1941 & 1945).

The 1949 report on "Forestry and Water Supplies in South Africa" included the following conclusions:—

"The fragmentary and contradictory nature of the evidence which has been presented, demonstrates clearly that the time has not yet come to draw final conclusions as to the effects of forestry on water supplies. The danger of over generalization has also been demonstrated. Certain *tentative* general conclusions do, however, appear to be justified and these are set forth here, although it is fully realised that they may have to be revised when more complete data are available. There has been much loose talk on this subject and, on the other hand, reliable results from controlled analytical research are not yet available. The following conclusions therefore merely attempt to summarise briefly the least problematic results of general experience and observation."

"1. Plantations of exotic trees, grown to timber size, will probably *not* use more water than indigenous forests, if they are on comparable sites.

2. Plantations of exotics and indigenous forests, will probably use more water than *fynbos* (sclerophyll scrub) or grass communities. The magnitudes of the differences are not known, but in the case of plantations they will probably be greater the more conditions deviate from those in true, moist, high-forest regions.

3. The consumption of water by plantations, forests and other plant communities, will depend chiefly on the amount of water available in the soil.

4. Plant communities of the same ecological order, that is, occupying similar positions in the succession of vegetation, will probably use approximately equal volumes of water.

5. Swamps and vleis tend to be dried up if trees are planted in them, and *also* if the natural succession progresses as far as the forest climax. The water is constantly *available* or accessible to the roots of the trees, because it is stagnant or nearly so.

6. There is no evidence that fast-growing tree species use more water than slow-growing ones—all other factors being equal.

7. The removal of vegetation—natural or artificial—from catchments, especially along stream banks, will cause an increased discharge from streams. The advantage is probably temporary, because it depends on the retention of deep soils rich in humus, which is impossible without a good cover of vegetation.

8. Heavy ground-covers provided by plantations and forests retard floods, build up and conserve soils."

This report also contained a number of recommendations in regard to afforestation, i. e.:—

"1. Extensive afforestation should not be undertaken, unless there is a reasonable chance of making a good profit on the money invested, or if there is not some other convincing local reason demanding the establishment of trees, for example, hut-pole growing in native territories to reduce exploitation of natural forests; aesthetic reasons; firewood production on farms; or provision of shelter for stock.

2. Afforestation should as far as possible be restricted to forest regions with high rainfall. There are many areas in South Africa where extensive afforestation should not be encouraged.

3. From the water conservation point of view, long rotation timber crops should be preferred to short rotation, quick-profit crops such as eucalypt-coppice for mine props, or wattle for tanning bark. In making this statement the important economic role of such crops is not lost sight of. Sites for these crops should however be selected with care.

4. Where the discharge of streams is used for irrigation, industrial or municipal purposes, moist areas along streams should not be planted up. This has been Forestry Department policy since 1932.

5. Tree-planting is not Forestry. Sound silvicultural practice and management on a sustained yield basis, are essential, and if these are not introduced the effects may be harmful on even the most suitable sites."

Current Conclusions

A few additional experimental results have become available since 1949 (Beard, 1956; Rycroft, 1952 & 1955), further general experience has been gained and conclusions, derived largely through deductive reasoning, have been published (Gevers, 1950; Wicht, 1959 (b)). None of the additional evidence is in conflict with the conclusions drawn in 1949.

The data published by Beard on rainfall interception and surface run-off in a plantation of *Acacia mollissima* Willd. compared with open grassveld in which the main species were *Aristida junciformis* and *Themeda triandra* are tentative, and Beard stresses "that none of the figures can be considered as of absolute accuracy." They tend, however, to support the second conclusion given in the 1949 report.

Rycroft's analyses of some data from Jonkershoek published in 1952, produced negative results, but this is, in itself, important, because although he found that the methods of recording and analysing the data were reliable, he could not disprove the *nul* hypothesis, viz., the development of a twelve-year old stand of *Pinus radiata* D. Don. in a catchment area in place of indigenous shrub vegetation has no effect on stream-discharge. He concludes as follows: "At most, however, it can be stated that no detrimental effects have thus far been observed as the result of establishment and growing valuable crops of timber at Jonkershoek."

In a paper published in 1955, Rycroft describes an experimental study of the effects of the removal of indigenous riparian vegetation along the banks of an open irrigation furrow for a portion of its length. The increased discharge brought about by this treatment proved to be statistically very highly significant and was of such magnitude that he suggested the removal of such riparian vegetation as a practical measure to improve water yields during periods of acute water shortage. These results support the seventh conclusion given in the 1949 report, and, in view of results obtained in America and elsewhere, there can be no doubt that the removal of phreatic vegetation significantly reduces vapour-losses

Gevers' paper in 1950 is largely a review of the 1949 report in which, after a general discussion of the problem he concurs with the conclusions drawn and commends the recommendations in regard to future afforestation.

In a paper on "The Management of Water Catchments" (Wicht, 1959), it was attempted to summarize the scientific foundations of catchment management and the practical measures for achieving the efficient management of catchments.

The need for studying water catchments as *eco-systems*, or "combinations of relationships", characterised by the reciprocal dependence of all the organic and inorganic components within the whole was emphasized. In general, the magnitude of the hydrological influences of forest biocoenoses within such eco-systems were stated to be related to their density. Climax development of the succession, due mainly to considerable *vapour-losses* caused by precipitation-interception and transpiration, "reduces the flood peaks, the intensity of discharge generally and the total stream-discharge from a catchment, and, where long dry seasons occur, it may, also—particularly through the function of phreatic vegetation—cause rapid recession of ground-water discharge in streams and reduce the low-water yield towards the end of the dry season. Decrease in the density of biocoenoses, even to the extreme of leaving no living cover, will increase the peaks of spates, the intensity of discharge generally and the total stream discharge from the

catchments, and, because the movement of water is unimpeded, immediate and rapid, will eventually lead to cessation of stream discharge in dry periods."

For achieving efficient management of water catchments, it was recommended that they should be assessed from the point of view of flood control and water yield utilization for power production, irrigation, industrial, municipal and domestic purposes and agricultural or forestry crop production within their limits, and classified in the following groups :—

"*a.* Maximum total clear stream discharge required for maximum possible storage in reservoirs;

b. Maximum stabilized stream discharge required for utilization without storage;

c. Relatively stable stream-discharge required for partial storage in reservoirs as well as direct utilization within and below the catchment;

d. Minimum stream discharge and maximum use of water within the catchment required."

Catchments in group *a.* would require minimum vegetal cover commensurate with erosion control or the artificial maintenance of stability within the catchment. The promotion of infiltration and augmentation of underground water is less important here. Afforestation should be precluded and natural forests and phreatic vegetation reduced or removed.

For catchments in group *b.* stability of stream discharge is essential. Promotion of infiltration without the excessive increase of vapour-losses is needed so that base flow discharge in streams will be increased and prolonged. Appropriate treatments should ensure the maintenance of deep soils of healthy physical structure to serve as aquifers releasing water to streams and underground resources. It is doubtful whether this condition could be achieved under forest cover in South Africa because of high vapour-losses during lengthy dry periods.

The catchments in group *c.* will serve multiple purposes and each will have to be separately judged according to the extent to which direct uitilization of water within or below the catchment or storage of water yields deserves priority. Most catchments will be allocated to this group. They will require mixed treatments, i. e. maintenance of forests or other dense or relatively dense vegetal cover in parts and reduction of vegetation in various ways elsewhere, or general treatments intermediate between those applied in catchments of groups *a.*, *b.* and *d.*

Within catchments of group *d.* it should be attempted to "use the water where it falls" through land-use planning, including total protection, forestry and conservation farming. Forests or other forms of climax natural vegetation should preferably be maintained.

Experience has been gained on which treatments for catchments in groups *a.* and *d.* can be more or less satisfactorily prescribed, but quantitative hydrological data to form a basis for recommending the treatments of those in groups *b.* and *c.* are particularly urgently needed and these can be derived only from planned experiments.

Existing knowledge does not warrant more than that these general recommendations should be added to those incorporated in the 1949 report. It will be interesting to learn whether experience in other parts of the world supports or invalidates these conclusions and recommendations.

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ON THE QUANTITY OF SNOW LODGING ON BRANCHES OF TREES IN PINE DOMINATED FOREST ON JANUARY 16, 1959, DURING THE TIME OF SNOW DESTRUCTIONS IN FINLAND

by M. SEPPÄNEN

Abstract

In a pine dominated forest of normal thickness the quantity of snow lodging on branches of trees may exceed 2,600 kg in weight on an area of 100 m².

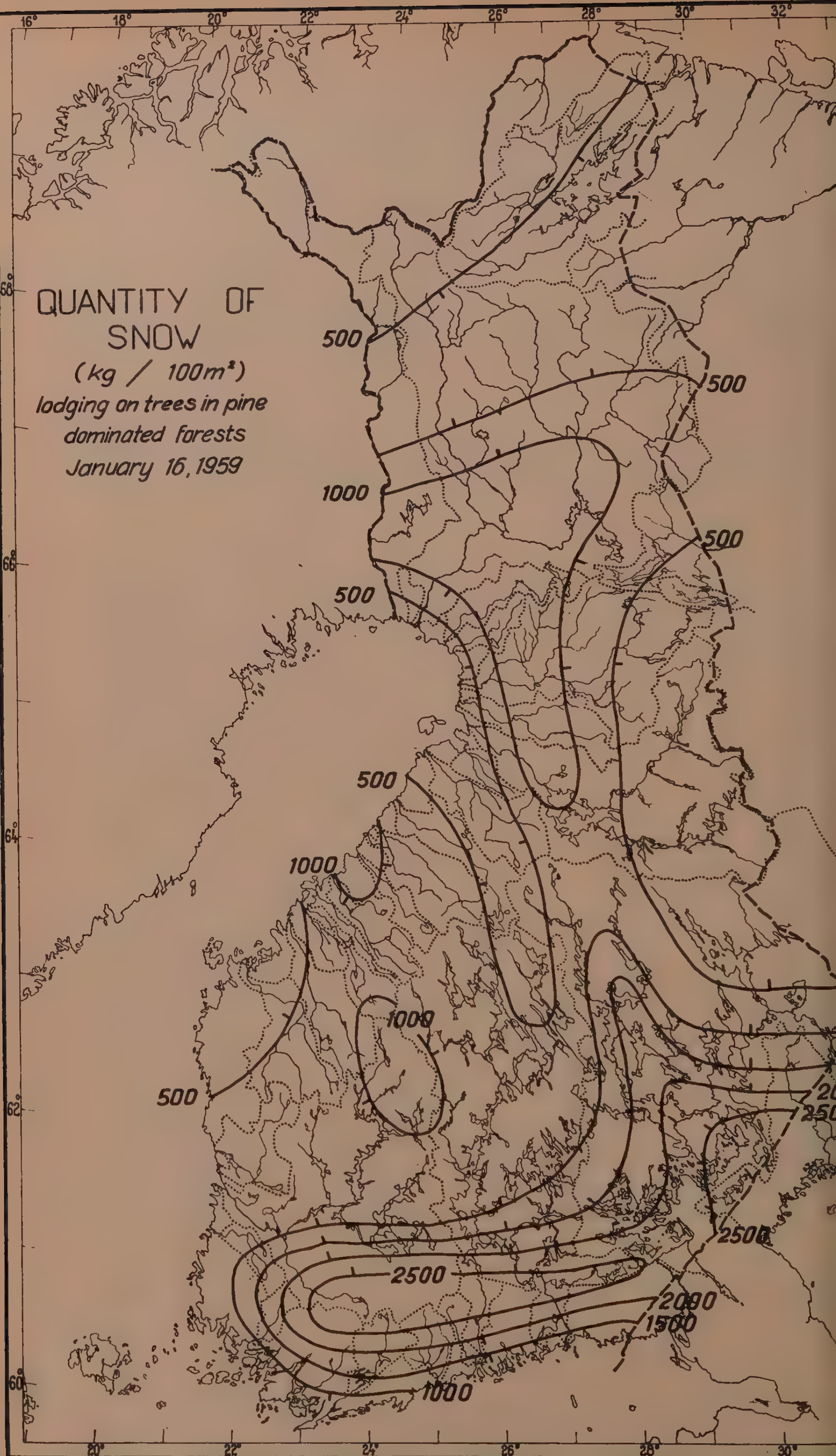
Résumé

Dans une forêt d'épaisseur normale où dominent les pins, la quantité de neige retenue par les branches des arbres peut dépasser 2600 kg en poids sur une surface de 100 m².

In forests in Finland great destruction done by snow occurred during the earlier part of January 1959, brought about by snow fastening to the branches of trees, the phenomenon having a ruineous effect particularly on the unthinned pine groves owing to the great weight of snow. The occurrences of greatest destruction were limited to an area located between 60° and 62° N latitude and 23° and 28° E longitude respectively. On January 16 there was as yet in general plenty of snow on the branches of trees, and an approximate picture of the quantity of snow lodging on branches can be obtained from the results provided by snow measurings carried out at the same date at snow course stations of the Hydrological Office.

TABLE — *Approximate quantity of snow on pine branches at snow course stations within snow destruction area on January 16, 1959.*

Snow station	Lat. N	Long. E	Weight of snow lodging on pine branches kg / 100 m²
Mellilä	60.8°	22.8°	4,500
Jokioinen	60.8°	23.5°	3,000
Hauho	61.3°	24.3°	1,400
Läyliäinen	60.6°	24.5°	1,800
Orimattila	60.8°	25.5°	4,000
Kausala	60.9°	26.2°	3,100
Iitti	60.9°	26.5°	1,700
Inkeroinen	60.6°	26.8°	1,500
Lappeenranta	61.1°	28.1°	2,400
			M = 2,600


QUANTITY OF SNOW
(kg / 100m²)
lodging on trees in pine dominated forests
January 16, 1959
16°
18°
20°
22°
24°
26°
28°
30°
32°
68°
66°
64°
62°
60°
500
1000
1500
2000
2500

When subtracting the water content of snow cover calculated for pine dominated forest from the calculated mean value of water content of snow cover of open fields, glades, and birch dominated forest at the same snow station, a difference will be obtained which is expressed in kg. on an area of 100 m^2. Same kind of calculations are carried out for each snow station separately. Results obtained are marked on a map and isolines are drawn for the same weight of snow lodging on trees, as illustrated in the map below.

As even at snow stations close to each other the calculated values of the weight of snow on trees differ considerably, the values were adjusted before drawing the isolines. In table below are shown the quantity of snow lodging on trees calculated from the results obtained from snow measurings carried out at snow course stations on the area of maximum snow destruction.

The mean value obtained from the table, agrees fairly well with the map. Thus, all considered, in all probability, in some pine dominated forests of normal thickness on the area of snow destructions the snow lodging on pines on January 16, 1959, exceeded 2,600 kg. on an area of 100 m^2 and probably even more in such unthinned pine groves there the greatest destruction done by snow had occured.

ON A NEW METHOD OF MEASURING SNOW COVER IN FOREST IN FINLAND

by M. SEPPÄNEN

ABSTRACT

The influence of various densities of forest on the water content of snow cover is different in forests of different thickness.

RÉSUMÉ

L'influence de diverses densités de forêt sur la teneur en eau de la couverture de neige varie avec l'épaisseur des forêts.

In Finland the determination of the average water equivalent of snow cover of river basins is based on snow measurings, which are done in different kind of terrain throughout the country by observers of the Hydrological Office on which the duty of the estimation of measurings devolves. As at least 60 % of the area of Finland is covered with forests the snow cover in them particularly calls for special attention. This estimation has proved to be quite a difficult task. Were the ground in forest ever so even the snow cover lying on ground at the same time in different places close by may differ considerably. The reasons may be many, of which will be mentioned here the snow being caught by branches and turbulence caused by trees.

As the previous methods of snow measurings, which mostly have been snow courses, did not explain the influence of single trees on the unevenness of snow pack in forest, new kind of snow measuring method was started as an experiment by the author. In cooperation with Oulujoki Oy two snow stations were grounded in 1955 in different parts in Finland. Those snow stations were set up in pine dominated forests on even ground where 108 calibrated sticks for reading the snow depth were set in 9 rows 10 meters apart, with 12 sticks in each row also 10 meters apart, all in good time before the beginning of the winter.

Thus the area of the whole measuring site was at both locations $80\,m \times 110\,m = 8800\,m^2$. All the brushwood supporting the snow was removed around the sticks by a radius of 1,5 meters. The calibrated sticks were inserted into the ground with the zero points accurately at the same level with the ground. Of the measuring sites maps were drawn and the lie of all the trees on the area as well as trees near by were duly marked, likewise the size and the species of trees. At the time of measuring the observer was to go skiing through the area so as not to brake the surface of snow too roughly, and to be careful of not coming unnecessarily near to the sticks. At the same time 16 snow density measurings were to be carried out at points fixed in advance for the points of those measuring places in relation to trees to be known. Snow measurings were to be done 6 times monthly starting from the middle of winter and carried on until the snow had vanished totally from the vicinity of all the sticks.

Measurings carried out at these stations afforded positive results to such a degree that the Hydrological Office started in summer 1958 in

MERIJÄRVI SNOW STATION

Map showing the lie of trees in relation to calibrated sticks

different parts in Finland similar kind of smaller snow stations, 17 in numbers, which were in action in winter 1958-59. At these stations there are in pine dominated forest 25 calibrated sticks in 5 rows 10 meters apart and in each row 5 sticks also 10 meters apart. The measuring sites were selected from a place in the forest with varying thickness for getting the influence of single trees on the snow pack to stand out more distinctly. The map enclosed shows the lie of the trees at one of the stations.

In addition to the measuring site in forest, at each such snow station 9 calibrated sticks were set up in 3 rows, 3 sticks in each row, all 5 meters apart on an unshielded open field on even ground. When selecting such open field measuring sites pains were taken to avoid places too much exposed to winds and the sticks were set up at such a distance from trees and buildings that the measuring site would not become in shadow, at least not at a time when the solar radiation was expected to have some influence on the snow pack. The purpose of such arrangement was to obtain information for permitting comparison of the snow situation and the development of it, especially at the time of melting, on one hand from open field and forests and on the other hand from measuring sites in different parts in Finland. Snow measurings were carried out in the same manner as at the bigger stations. The density of snow was measured at 4 points in forest and at 2 points on the field.

As an addition to the snow course measuring stations and other snow stations those new stations improved the possibility to follow the development of snow pack and especially the melting of snow in spring. Furthermore, as the winter 1958–59 in Finland happened to be very exceptional in many ways the additional information obtained from the new stations proved to be highly acceptable.

On the utilization of the results obtained from these snow stations a following mode of application will be presented.

In December 1958 and in January 1959 the branches of trees were in general covered with plenty of snow. By the beginning of February the snow had vanished from the trees by falling down to the ground mostly. Accordingly the water content of snow cover on the ground in forest had by the beginning of February increased for two reasons: by the effect of snow fall (precipitation) and by snow that had fallen down from the trees. In the following the influence of the thickness of forest on the water content of snow cover during that time will be examined. It will be noted.

w = water content of snow at one of the calibrated sticks in forest.

w_0 = average water content of snow on the measuring site in forest.

n = number of pines on an area of 400 m² surrounding the stick mentioned above.

n_0 = average number of pines on an area of 400 m².

$\triangle w = w - w_0$

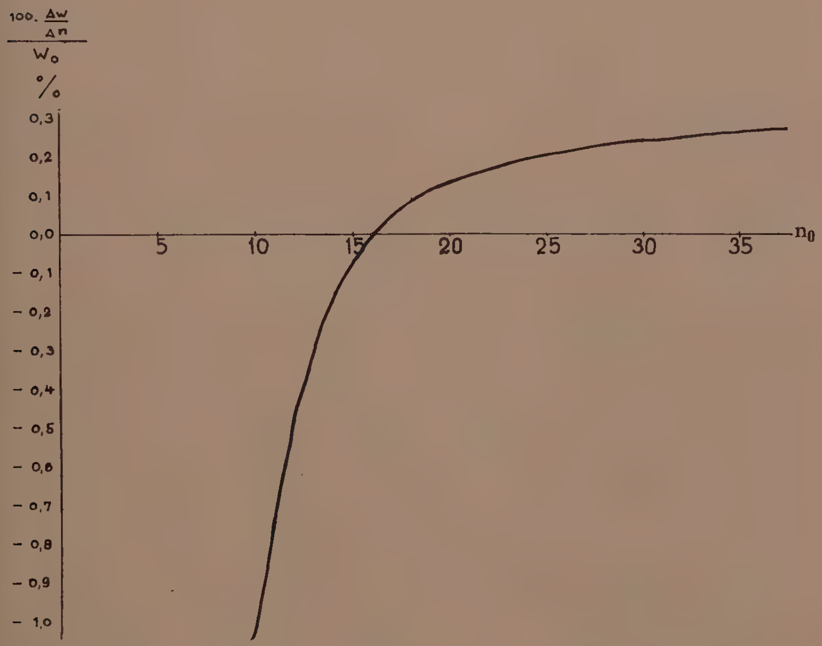
$\triangle n = n - n_0$

Values $\triangle w$ and $\triangle n$ are calculated for all the calibrated sticks in forest and of these such a ratio $\frac{\triangle w}{\triangle n}$ is determined, which in best manner will fit the pairs of values $\triangle w$ and $\triangle n$. Ratios are formed separately for each station and indicated as percentage of w_0. The percentage $(100 \cdot \frac{\triangle w}{\triangle n} : w_0)$ is then plotted against values of n_0 of the measuring sites of different stations.

A curve given below is obtained, showing approximately the influence of the increase of one tree respectively upon the alterations in water content of snow cover in forest of different density in the beginning of February 1959.

According to the curve at snow stations there the density of forest was n_0 = 16 trees / 400 m² the average result of measuring did not depend on the location of the measuring site, whether in denser or thinner part of the forest, owing to the fact, that even if at previous precipitation there had fallen more snow on the ground in the thinner parts of the forest, later the corresponding greater quantity of snow falling down from the trees in the

denser part of the forest compensated the differences. Furthermore, at such snow stations there $n_0 < 16$ trees / 400 m², in thinner parts of the forest the snow that had fallen on the ground during snow fall exceeded the quantity of snow in denser parts of the forest to such a degree that the snow fallen from the trees could not compensate the differences. On the other hand at snow stations there $n_0 > 16$ trees / 400 m² in thinner parts of the forest the increase in snow cover on ground owing to precipitation was so much slighter, that the increase in water content of snow cover owing to the snow fallen from the trees in the thicker parts of such a forest was greater than in the thinner parts.



Alteration in water content of snow cover as a function of the density of forest in the beginning of February 1959

EFFECT OF FOREST AND FOREST STRIPS ON THE MOISTURE CONDITIONS OF SOILS AND GROUND WATER LEVELS IN THE FOREST-STEPPE AND STEPPE DISTRICTS OF THE UKRAINE

by **I. T. GRUDINSKAYA** and **I. S. SHPAK**
Chief Geological Administration of the Ukrainian SSR

Summary

I. In the Black Forest (southern outskirts of forest-steppe, plateau, podzolized chernozyom on loess, crushed stone, depth of occurrence of ground waters over 12 m):

1) the soil moisture at a depth of 0.1-0.5 m is usually greater in the forest than in the field; at a depth of 1-8 m it is always greater in the field than in the forest by 5-7 per cent and at a depth of 12 m the difference between the moisture in the field and in the forest, gradually decreasing, is only 1-2 per cent;

2) in 1954-1958 feeding of ground waters by meteoric waters was observed only in the field, on the forest edge and on cleared spaces, and then only in the winter—spring period and not every year;

3) in the forest drenching was noted only in the upper soil layers, and because of this ground water under forest can be fed only by lateral flow of water from the forest edges and woodless sections;

4) replenishment of the ground waters under forest by flow from the adjoining woodless sections is confirmed by the inclinations of the ground water table (from 0.001 to 0.01) in a direction from the woodless sections to the middle of the forest range and by the rise in mineralization of the ground waters under the forest to a value twice as high as under the field;

5) a consequence of the dependence of the ground water level under the forest on the level of the water of adjoining sections is that acute and prolonged anomalies in the quantity of precipitations affect the depth of ground water occurrence under the forest somewhat later than that under the field and the woodless section, and more evenly;

6) in the heart of the forest the ground waters occur at 3-5 metres or lower and have a narrower range of fluctuation than on the edge of the forest, in glades and in the field;

7) cutting down the forest in isolated sections in the heart of the forest range leads to a rise in the ground water level under conditions when a general fall in the levels is noted.

II. In the Krasnyansk wood plot of the Trostyanets forest (forest-steppe slope of the Boromli river valley, consisting of sands, pine forest, ground water depth 2-9 m):

1) seepage of meteoric water goes on throughout the investigated area;

2) the relative change in the ground water level in the forest and on the woodless section depends chiefly on the precipitations of the same year;

3) in the 50-150 m forest strip directly adjoining the woodless section and located above it on the slope, the ground water level is at lower marks than in the woodless section.

III. In the Veliko-Anadol area (steppe zone, undulating watershed plateau, soil—ordinary chernozyom on clayey loess, system of forest strips of the Mariupol experimental forestry station):

1) percolation of meteoric waters and feeding of ground waters is observed on the territory of the forest strips and open sections during the winter—spring period;

2) under the forest strips the ground waters occur several metres higher than in the field, which is due to supplementary sources of moisture because of retention of snow drifting from the woodless spaces and the absorption of the surface flow from adjoining fields;

3) the ground water level rose almost continually during three years of observation (1956-1958) in the open drainage area. In the forest strips and near them, regular seasonal fluctuations were observed with a rise in spring and an abrupt fall during the summer.

IV. An analysis of the data of observations conducted on the Black Forest, the Trostyanets forest range and the forest strips in the Veliko-Anadol area fully substantiate the conclusions of P. V. Ototsky and G. N. Vysotsky to the effect that the ground waters occur at a greater depth under the forest than in the woodless sections, as well as G. N. Vysotsky's conclusions as to the desiccating role of the forest ranges in the steppe and forest-steppe districts of the Ukrainian SSR and the beneficial effect of forest strips on the soil moisture and ground water conditions.

V. I. M. Labunsky's assertion as to the favourable effect of forests on the increase of ground water reserves, both under forest and in adjoining areas, is erroneous.

VI. The average annual value of the ground water level in the Veliko-Anadol forest depends directly on the average annual precipitations calculated for the decade preceding the year of observations of the level.

Résumé

I. Dans la « Forêt Noire » sur un plateau avec la nappe aquifère à 12 m de profondeur :
  a) la teneur en humidité est supérieure sous les forêts dans l'épaisseur comprise entre 0,1 et 0,5 m. Elle est au contraire supérieure de 5 à 7 % sous la campagne libre à des profondeurs comprises entre 1 et 8 m. Ce pourcentage est ramené à 1 à 2 % à une profondeur de 12 m.
  b) de 1954 à 1958, la nappe aquifère ne fut alimentée par les eaux météoriques que sous la campagne libre, les clairières et aux coins des forêts. La recharge de la nappe sous la forêt par le flux latéral venant des champs est établie par la configuration des pentes de la nappe. Une conséquence de ce genre d'alimentation est que les anomalies dans la production des précipitations se répercutent plus tardivement dans la nappe sous les bois que sous les champs.
  c) D'autre part au cœur de la forêt, le niveau de la nappe souterraine est de 3 à 5 m plus bas qu'en plein champs et l'amplitude de la fluctuation y est plus réduite.
  d) la coupe des arbres dans une région isolée au cœur de la forêt y provoque la montée de la nappe quand celle-ci s'abbaisse sous la forêt.

II. Dans la forêt de Krasnyansk sur un terrain sablonneux en pente, la nappe est plus fortement déprimée dans la bande de 50 à 150 m. située au-dessus de la forêt sur la pente.

III. Dans la région Veliko-Anadol (plateau ondulé), le niveau de la nappe sous la forêt est plus élevé qu'ailleurs par suite de l'alimentation complémentaire sous l'action de l'accumulation de la neige chassée des régions ouvertes et par suite aussi de la dérivation vers la forêt d'eaux superficielles venant des champs.

IV. En résumé, dans les trois zones étudiées, les constatations confirment que la nappe est plus profonde sous la forêt qu'ailleurs. Toutefois, les considérations de Vysotsky sur le rôle bénéfique des bandes forestières sont confirmées.

V. Les assertions relatives au rôle toujours bénéfique de la forêt sur l'accroissement des réserves d'eau souterraines sont controuvées.

VI. Le niveau moyen de la nappe sous la forêt de Veliko-Anadol dépend de la moyenne annuelle décimale des précipitations pour les 10 années précédant la production du niveau.

The question of the effect of forests on the ground water conditions and, especially, on the moisture conditions of soils in the forest-steppe and steppe districts of the Ukraine has been dealt with in numerous scientific papers. The review and critical appraisal of this literature may well be the subject of an independent study.

In this report we shall discuss only those researches which are concerned with the districts of our investigations.

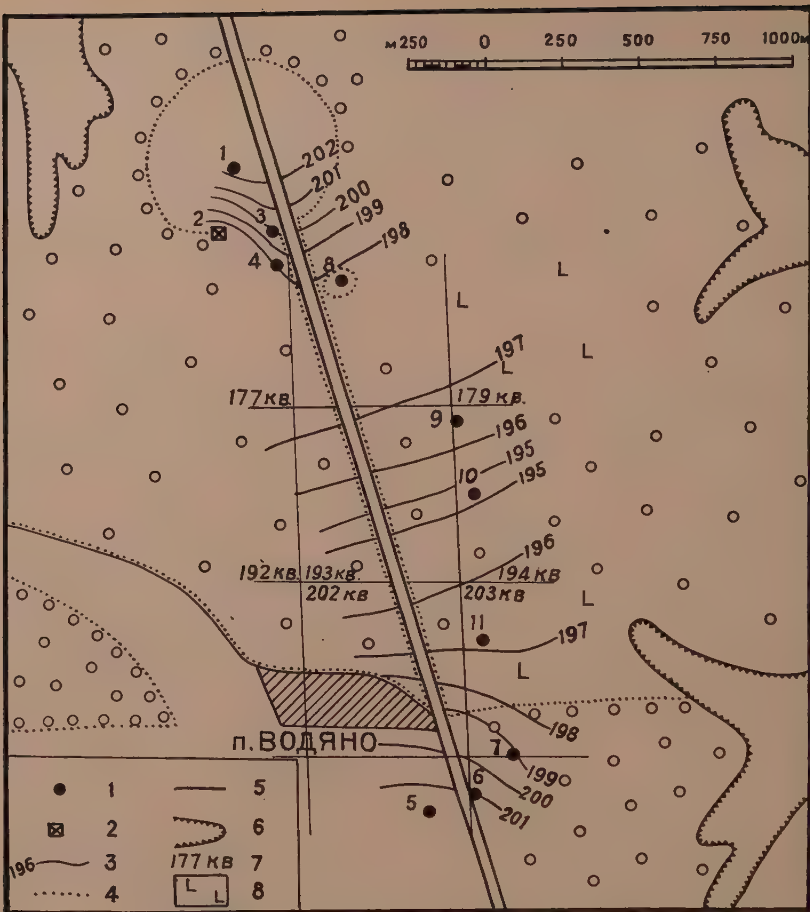


Fig. 1 Schematic diagram of location of observation boreholes in the Black Forest area.

1—borehole and its number; 2—well; 3—hydroisohypses of the average annual ground water level for 1954; 4—forest boundary; 5—boundaries of forest divisions and cleared spaces; 6—contours of gullies; 7—number of division; 8—brushwood on space cleared in 1950.

In the Black Forest district investigations of these problems have been conducted by Bliznin G. Y. ([1]), Ototsky P. V. ([11]), Shorodumow A. S. (14, 15), Pogrebnyak P. S. (13) and others; in the Trostyanets forest range, by Falkovsky P. K. (17), Vysotsky G. N. (4), Gotschalk Y. S. (5), Pavlenko I. A. (12) and others; in the Veliko-Anadol forest and the forest strips of this district, by Vysotsky G. N. (2, 3, 4) and Labunsky I. M. (7-10).

The present report outlines the results of observations conducted by the North Ukrainian State Hydrogeological Station in 1954-1958 in the Black Forest and the Trostyanets forest range, as well as the results of observations

of the Veliko-Anatol Draining Station of the Hydrometeorological Service of the Ukrainian SSR during 1955-1958.

The Black Forest is the last large forest island in the steppe. The forest range, covering an area of 8350 hectares, extends almost 14.5 kilometres

TABLE 1

Aqueophysical Characteristics of Soils

Depth in cm	Volume weight field	Volume weight forest	Specific weight field	Specific weight forest	Wilting Moisture in per cent field	Wilting Moisture in per cent forest	Least moisture-holding capacity in per cent field	Least moisture-holding capacity in per cent forest	Full moisture-holding capacity in per cent field	Full moisture-holding capacity in per cent forest
					Black Forest					
0— 5	1.24	0.78	2.57	2.50	11	12	30	43	42	88
5— 15	1.23	1.12	2.59	2.59	11	12	28	30	42	51
15— 25	1.31	1.26	2.62	2.67	11	12	26	23	38	42
40— 50	1.31	1.39	2.67	2.69	11	9	24	22	39	34
65— 75	1.38	1.44	2.69	2.69	11	9	23	23	35	33
90—100	1.34	1.40	2.69	2.69	10	9	22	26	36	34
115—125	1.32	1.35	2.71	2.70	10	9	—	23	39	37
140—150	1.34	1.35	2.69	2.70	—	9	—	23	37	37
190—200	1.41	1.45	2.68	2.70	—	9	—	23	34	32
240—250	1.40	1.39	2.73	2.70	—	10	—	23	35	34
290—300	1.42	1.39	2.70	2.70	—	9	—	—	33	36
340—350	1.37	1.44	2.69	2.69	—	8	—	20	36	32
390—400	1.43	1.47	2.69	2.69	7	7	—	18	33	31
440—450	1.45	1.50	2.69	2.69	7	7	—	16	32	29
490—500	1.47	1.47	2.70	2.68	5	5	—	16	31	31
					Veliko-Anadol					
0— 10	1.02	0.95	2.67	2.60	15	16	—	34	53	60
10— 20	1.11	1.05	2.67	2.61	—	15	—	33	51	53
20— 30	1.10	1.07	2.66	2.63	16	18	—	30	51	49
30— 40	1.05	1.13	2.68	2.64	16	16	—	30	56	46
40— 50	1.10	1.19	2.67	2.67	—	16	—	29	49	44
60— 70	1.24	1.33	2.70	2.72	16	18	—	28	37	37
80— 90	1.35	1.37	2.71	2.70	14	16	—	26	33	35
100—110	1.26	1.37	2.74	2.74	14	14	—	25	39, 33	33
120—130	1.39	1.43	2.74	2.75	13	12	—	24	31	29
140—150					—	—	—	23	—	—

NOTE: for the Black Forest district most of the aqueophysical characteristics are given from the data of V. M. Slovikovsky and Y. K. Zarudny (Forestry Institute of the Ukrainian SSR Academy of Sciences). The wilting moisture for the forest section is obtained from the maximum hygroscopicity by multiplying by 1.35; for the field, from the data of experiments in vegetational pots. The full moisture-holding capacity is computed from the volume and specific weights.

For the Veliko-Anadol draining station the least moisture-holding capacity is taken from the results of field determ nations by the method of flooding areas, carried out by the laboratory of the Ukrainian Hydrometeorological Service; the other characteristics, from the data of N. K. Sofoterov and N. G. Iovenko (16).

from northwest to southeast on the rightbank watershed plateau of the Ingulets river (Kirovograd region).

In the northwestern part of the forest the width amounts to 7.5 kilometres; in the southeastern part, 2.8 kilometres.

The predominant species is oak from 40 to 70 years of age; in addition hornbeam grows here, more rarely—elm and maple.

The district of investigation is in the central part of the forest near the town Vodyano on a perfectly level plateau (fig. 1).

The soils are podsolized chernozyom (black soil) and grey forest soils. The lower horizons of the soil turn into loess, which from 2 to 3.5 m is brown, loamy and limy; lower down, 6 to 8 m, tawny, sandy-loamy. At a depth of from 6-8 to 10-12 metres, there are beds of reddish brown, loess-like weakly limy loam (buried soil?); still lower, up to 13-16 m, there is a tawny loamy loess with numerous limy inclusions. This series is underlain by reddish-brown dense limy clay.

The water-bearing horizon is found in the lower parts of the loess series and the reddish-brown clays.

The ground waters in the Black Forest area occur at a depth of 12-17 m.

The aqueophysical characteristics of he soil are presented in Table 1 (see page 255); the granulometric composition in Table 2.

The change in the ground water levels under forest, on spaces cleared in 1950, in the fields and glades is an even one, without any abrupt episodic fluctuations (fig. 2a). During the period under discussion no rise in the levels was noted in the forest or glades, even after spring thaws and abundant rains. An exception is borehole 7, where seasonal fluctuations were observed with minimum levels in October—January and maximum in June—August. In the other boreholes a fall in the level occurred, as a rule, in the course of the year. The range of the annual change in the ground water level in the forest did not exceed 0.3-0.5 m.

TABLE 2

Granulometric Composition of Soil (1)

Depth in cm	Percentage content of fractions size (mm)				
	0.25—0.05	0.05—0.01	0.01—0.05	0.005—0.001	< 0.001
			Black Forest		
10— 20	5	43	9	10	33
20— 30	4	44	9	10	33
30— 40	5	46	8	10	31
50— 60	4	47	8	9	32
80— 90	5	46	9	9	31
			Veliko-Anadol		
10— 20	1	24	11	16	48
40— 50	0	24	12	14	50
70— 80	1	25	11	15	48
111—120	1	25	10	15	49
141—150	1	25	11	15	48

(1) According to data of the Ukrainian Hydrometeorological Service.

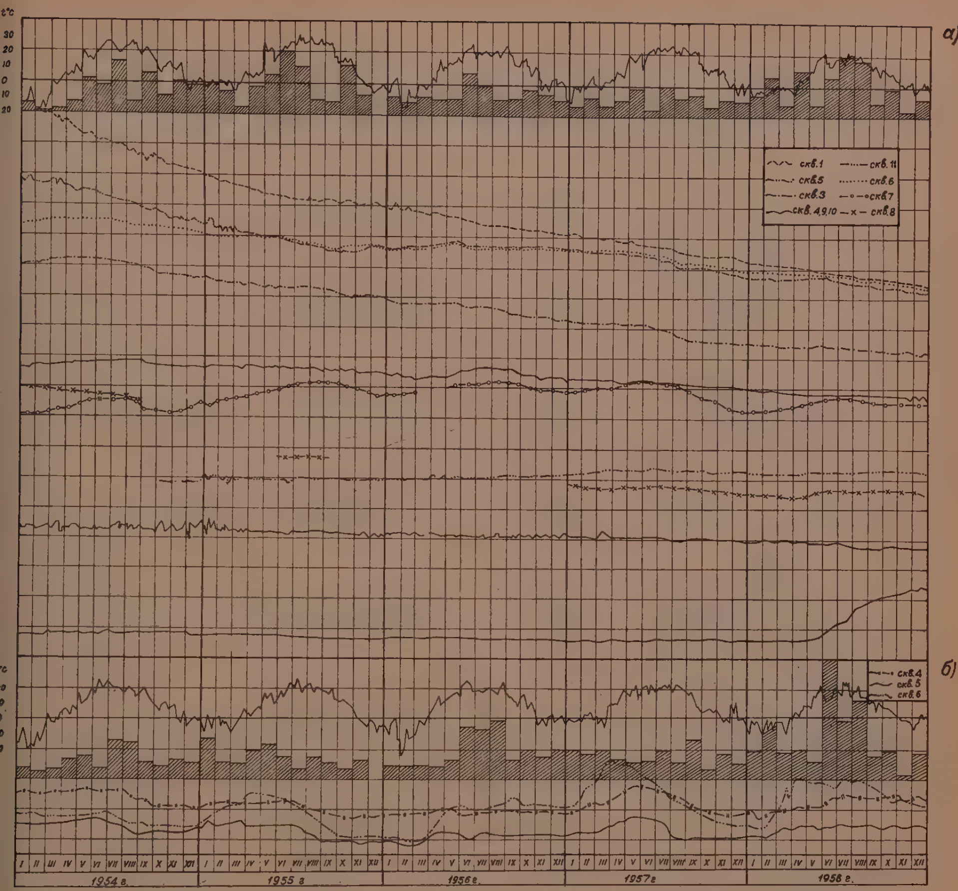


Fig. 2 Change in ground water levels in the area of a) the Black Forest and b) Krasnyansk forest plot of the Trostyanets range. Boreholes 4, 9 and 10 located on the boundary from top to bottom.

The least range of annual fluctuations of the level (0.1-0.2 m) is observed in the heart of the forest of 40-70-year-old trees (boreholes 4 and 10) and in a small glade surrounded by a similar forest (borehole 8).

In the field, the edge of the forest, and land cleared in 1950 a slight rise was observed during the winter-spring period in some years, and in others a slower fall or an even course, but in particularly dry years (1957) the intensity of the decrease in level in the field and in the cleared space remained unchanged, and only on the edge of the forest did the fall in the level cease during the winter-spring period in all years.

The range of annual fluctuations of the ground water level in the field, the glades and the forest border is considerably greater than in the forest (Table 3). The greatest range is as much as 1.7 m, noted in the centre of Bolshaya Polyana.

TABLE 3

Ground Water Level

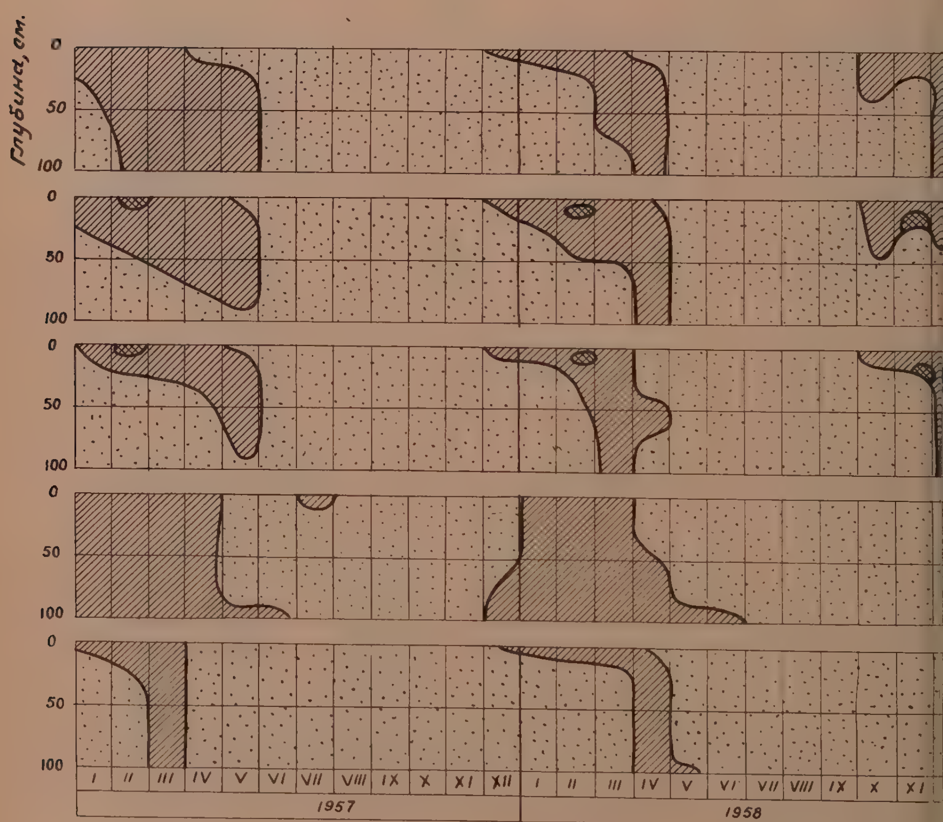
Bore-hole Nos.	Location	Absolute Mark mouth of borehole	Average annual level (depth from surface of earth) in metres 1954	1955	1956	1957	1958	Average in m	Annual variation Min-imum in m	Year	Max-imum in m	Year
					Black Forest,							
1	In centre of Bolshaya Polyana at Ototsky well No. 5	213.16	10.11	11.49	11.90	12.33	12.75	11.71	0.46	1957	1.69	1954
3	Edge of Bolshaya Polyana	214.60	14.12	14.48	14.79	15.14	15.41	14.79	0.14	1958	0.39	1957
4	Forest at Ototsky well, former div. 48	215.33	16.47	16.56	16.60	16.74	16.92	16.66	0.11	1958	0.20	1957
5	Field, 0.2 km from forest	213.68	12.18	12.79	12.81	13.09	13.43	12.93	0.21	1956	0.75	1954
6	Edge of forest	214.93	13.77	14.04	14.06	14.26	14.52	14.05	0.14	1958	0.38	1957
7	Forest	214.56	16.56	16.43	16.24	16.52	16.35	16.42	0.25	1956	0.57	1957
8	Small glade 10 km from forest	213.54	15.94	—	16.30	16.37	15.64	15.58	0.06	1958	0.32	1958
9	Border of space cleared in 1950	211.67	15.50	15.54	15.60	15.62	16.50	16.78	0.19	1957	0.20	1954
10	Forest	212.47	18.11	18.06	18.14	18.15	17.80	18.07	0.07	1954	0.92	1958
11	Young forest on space cleared in 1957	211.74	14.88	14.76	14.70	14.56	14.75	14.85	0.10	1957	0.31	1954

Bore-hole Nos.	Location	Absolute Mark mouth of borehole	Average annual level (depth from surface of earth) in metres					Average in m	Annual variation			
			1954	1955	1956	1957	1958		Minimum in m	Year	Maximum in m	Year
					Trostyanets Forest Range							
4	25-year old forest	119.84	8.22	8.30	8.39	8.25	8.23	8.29	0.24		0.45	
5	25-year old forest	116.96	6.27	6.35	6.43	6.30	6.28	6.33	0.28		0.39	
6	Woodless section 20 m from forest	114.55	3.75	3.58	3.68	3.35	3.34	3.54	0.38		1.15	
					Veliko-Anadol Draining Station							
5	Sukhoy ravine, middle of drainage area, right-bank slope	237.58	—	—	13.24	12.60	11.14		1.0	1957	1.8	1958
6a	Sukhoy ravine, upper part	246.91	—	—	19.46	18.66	18.06		0.6	1957	1.4	1956
4	Dubovy ravine, lower part of drainage area, right-bank slope	240.24	—	—	10.66	10.30	9.80		1.1	1957	2.1	1956
5a	Dubovy ravine, middle of drainage area, right-bank slope	246.66	—	—	10.93	11.01	10.95		0.9	1958	1.4	1957

A fall in the levels was noted, as a rule, thoughout the period from 1954 to 1958 inclusively, an exception being borehole 11, located in the space cleared in 1950, where a slight rise in the level was observed in 1954–1957. Observations on borehole 10 also furnish evidence that change in the ground water conditions occurs in sections where the forest has been cleared. During January and February of 1957, five hectares of forest were cut 30 m from this borehole. The section was cleared of stumps and ploughed. As a result, an intense rise in the ground water level began in May 1958, amounting to 0.9 m at the end of 1958 (fig. 2).

The ground water level was lower in the forest than in the field, the glades and the edge of the forest, and at considerably lower absolute marks (fig. 1) in all boreholes throughout the entire period of observation. The greatest fall in the level on passing from field to forest occurs in the border belt of the forest. Here, the inclination of the ground water table is considerable and amounts to 0.01. In the heart of the forest the inclinations are 5–10 times less.

The presence of inclinations in the ground water table gives rise to a ground water flow from the unwooded sections into the heart of the forest range. In addition, the existence of ground water flow towards the forest



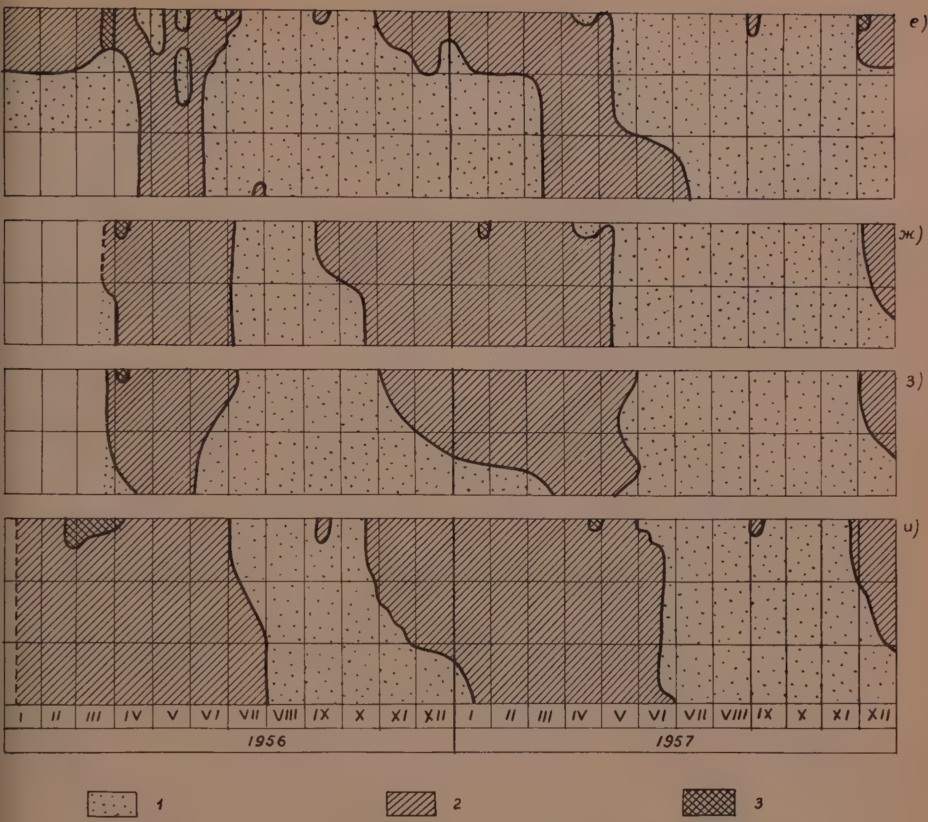


Fig. 3 Soil moisture in the Black Forest area: a) in the field at borehole 5; b) on the forest edge at borehole 6; c) in the forest at borehole 7; in the Trostyanets forest; d) in the field at borehole 6; e) in the forest at boreholes 4-5; at the Veliko-Anadol draining station; f) section 1 field; g) section 2, field between forest strips; h) section 3, forest strip; i) section 4, field between strips.

Soil moisture: 1—wilting moisture to least moisture-holding capacity; 2—least to full moisture-holding capacity; 3—higher than full moisture-holding capacity.

from the field is indirectly demonstrated by the values of the total mineralization of ground waters in the field and in the forest border, the figure being about twice as high under the forest than in the field section. This may have occurred because of the greater length of water migration from the moment of seepage into the soil.

Determination of the soil moisture was carried out monthly up to 1 m; and at a greater depth, four times a year: in February, May, August and November in the field (borehole 5), on the edge of the forest (borehole 6) and in the forest (borehole 7) by the weight method. Samples of soil were taken from within the first metre at intervals of 10 cm, beginning with the 5th cm, and at lower depths every 0.5 m; in summer (August) observations were

conducted up to the ground water level, and at other times up to a depth of 5 m.

From fig. 3 (a, b, c) it can be seen that the metre-deep soil layer is drenched (the soil moisture reaches values exceeding the least moisture-holding capacity) in the field both in 1957 and in 1958; whereas on the forest edge and in the forest this occurred only in 1958.

The duration of the drenching period decreases with the depth. At a depth of 1 m the duration of this period in the field varied from 1 to 4 months, and in the forest it did not exceed one month.

The samples were taken only once, therefore the results of the moisture measurements may at some periods prove to be accidental. The point is that the soil moisture varies with the depth unevenly, which is accounted for by the variability of the mechanical composition and other physical features of the soil within the profile; this makes it hard to reveal the actual moisture distribution by depth.

In view of this, the soil moisture values for all years (1954-1958) have been averaged by seasons (fig. 4) in order to compare the nature of the change in soil moisture for various seasons at great depths.

On comparing the soil moisture in the field and in the forest (fig. 4) substantial differences were detected in absolute figures, especially marked at the depths of 1-8 metres. Here, the moisture of the soil in the field was 5-7 per cent greater than in the forest. At a depth greater than 8 m the difference between the soil moisture in the field and in the forest decreases and at a depth of 12 m it amounts to only 1-2 per cent.

Fig. 4c shows that at a depth of 3.5 to 7 m the soil moisture values are relatively low. This is probably due to the fact that at this depth the soil consists of sandy loess; below and above, there are clayey varieties of loess possessing great moisture-holding capacity.

These peculiarities of the soil moisture conditions and of the ground waters in the Black Forest for 1954—1958 permit drawing the following conclusions:

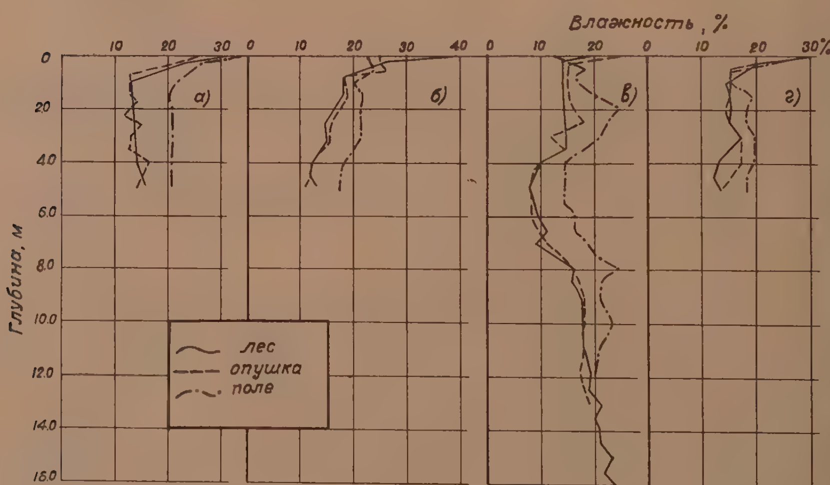


Fig. 4 Soil moisture in the Black Forest area in February (a), May (b), August (c), November (d).

1. Drenching is observed in the forest only in the upper soil layers, evidently due to the intense transpiration of arboreal vegetation as compared to the transpiration of farm crops on the fields adjoining the forest, in connection with which the ground waters under the forest may be fed only by the lateral flow of water from the forest borders and the woodless sections.

2. Feeding of ground waters was observed only in the field, on the edge of the forest and in cleared spaces during the winter-spring period of certain years.

3. The ground waters occur under the forest at a level which is several metres lower than in the field or large glades.

4. During periods with a considerable deficit of precipitation, the difference between the ground water levels in the field and the forest decreases, since at this time the atmospheric precipitations do not seep through to the ground water table, while the discharge into the lateral flow towards the forest continues.

5. In view of the foregoing, the periodic fluctuation of precipitation may be said to affect the ground water level with some delay in the forest, as compared to the field, while the magnitude of the fluctuations of the level in the forest is less than it is in the field.

6. Clearing the forest in separate sections in the heart of the forest range calls forth a rise in the ground water level in the course of a number of years even under conditions when a general fall in level is noted.

In the vicinity of Trostyanets (Sumy region), located in the northern part of the forest-steppe zone, observations were conducted in the Krasnyansk wood plot on the slopes of the Boromli river in a pine forest.

The soils of the aeration zone consist of fine-grained sands with interlayers of sandy loam occurring at various depths. The general inclination of the ground water table, established by nine boreholes, is directed toward the river. In the borehole farthest from the river the ground waters are at a depth of about 9 metres; while in the borehole situated closest to the river the ground waters occur at a depth of 1 metre.

For comparison of the ground water conditions in the forest and in the woodless section, the authors applied the results of observations of three boreholes (Table 3) located in a straight line perpendicular to the horizontals of the earth's surface. The distance between boreholes was 50-100 m.

In borehole 6, drilled on a woodless section in the railway right of way, the ground water level, expressed in absolute marks, was higher during the entire period of observation by 0.4-0.6 m, than in the wood in the vicinity of borehole 5, located at a lower point of the slope.

Furthermore, in periods with a raised infiltration of atmospheric waters in the soil (June 1956, July 1957, March-December 1958) the level of the water in borehole 6 exceeded even the level of the water in borehole 4, which was located in the forest at the upper end of the line (fig. 2b).

This circumstance confirms the conclusion drawn from observations in the Black Forest to the effect that the further one goes into the forest the greater the effect on the lowering of the ground water level.

In connection with the fact that the aeration zone consists of sandy soils, the feeding of the ground waters by infiltration is observed here every year and in all boreholes.

The relative changes in the ground water level in the forest and the woodless section depends mainly on the meteorological conditions of the year in question. Winter-spring rises in the level, beginning in January-March were noted annually during 1954-1958. The highest levels in the woodless section

were noted in April-May; in the forest, during May-July. Then a gradual fall usually sets in before the end of the year. During years distinguished by abundant summer-autumn precipitations (1956 and 1958) a secondary autumnal rise was observed in the woodless section; in the forest, however, a uniform change in the levels was noted in this case during the second half of the year.

Furthermore, the change in the water level in the woodless section occurred in the course of several days after thawing of the snow or abundant showers, but over a period of 1-3 months in the forest.

Observations of the soil moisture in the vicinity of Trostyanets were conducted in the three boreholes mentioned above, employing the same methods as in the Black Forest.

The lowest moisture-holding capacity, established by observations on the soil moisture in the spring, was 15 per cent for a depth of 0-5 cm; 10 per cent for 5-10 cm; 3 per cent for 10-30 cm; 7 per cent for 30-50 cm and 6 per cent at greater depths.

As can be seen from fig. 3 (d, e) drenching of a one-metre layer of soil in the woodless section and in the forest was observed in both 1957 and 1958. The duration of this condition was 3-4 months in the woodless section and not more than one month in the forest. During the summer-autumn period, the soil moisture does not attain values equal to the least moisture-holding capacity either in the observed sections or the Black Forest.

In the 25 cm layer the soil moisture in the field is lower than in the forest in August and November. In the other two periods of observation the field soil moisture is higher than in the forest in this layer too.

The magnitudes of the soil moisture fluctuations in the Trostyanets forest are slight both in respect to depth and in various sections. Only in the superficial 25 cm layer does the soil moisture sometimes exceed 10 per cent in November and February. From a depth of 0.5 m up to the upper boundary of the capillary fringe, the soil moisture fluctuates as a rule within limits of 2 to 5 per cent.

The following conclusions may be drawn on the basis of an analysis of the data on the Krasnyansk wood plot and the Trostyanets forest range:

1. the seepage of meteoric water occurs throughout the investigated territory;

2. the relative change in the ground water level in the forest and in the woodless section depends mainly on the precipitations of the given year;

3. in the 50-100 m strip of forest directly adjoining the woodless section and located above its slope, the ground water level occurs at lower marks than in the waterless section;

4. the soil moisture in the vicinity of the Krasnyansk wood plot is almost 1 per cent lower than in the Black Forest, which is accounted for by the mechanical composition of the soils.

Thus, despite the geomorphological, lithological and climatic differences in the areas under consideration (Black Forest and Trostyanets forest), the ground water level in the sections adjoining the forest are in both cases higher than in the forest. The soil moisture—beginning with a depth of 0.5 m and up to the upper boundary of the capillary fringe—is, as a rule, lower in the forest than in the adjoining woodless sections.

Lastly, let us examine the soil moisture conditions and the ground water levels under the forest strips and in the field, according to the observations of the Veliko-Anadol draining station (Stalino region).

In the Veliko-Anadol area observations were conducted on the watershed sections on the thoroughly ploughed drainage area of the Sukhoy ravine and

the drainage area of the Dubovy ravine. The latter is covered with forest strips of the Mariupol experimental forestry station. The area occupied by forest strips on this drainage area is 24 per cent. Farm crops are grown between the strips. The width of the forest strips is between 10 and 200 metres. The forest strips consist chiefly of oak plantations over 25 years old.

The soil is ordinary chernozyom. Everywhere under the soil lies brown argilaceous loess, with limestone inclusions occurring in places. At a depth of 3 to 12 m the loess contains an interlayer of buried soil consisting of reddish-brown or dark grey loam.

The loess deposits are underlain by destruction products of crystalline rocks, kaolin and crushed stone. The latter bed in the upper part of the ravines at a depth of 20—25 m, and in the lower part at 12—15 m.

The aqueophysical features of the soils are presented in tables 1 and 2.

Samples for testing soil moisture were taken with fourfold repetition once in ten days, as a rule, on the 8th, 18th and 28th of each month at 10 cm intervals of depth.

Soil moisture observation section 1 was situated on the gentle slope of Sukhoy ravine, on which maize grew from May 28 to September 29, 1956, and which was ploughed fallow the rest of the time. Section 2 was located on the right-bank gentle slope branch of Dubovy ravine 50 m from the forest strip. Up to August 28, 1956 it was ploughed fallow, afterwards winter wheat was grown. Section 3 was situated beside section 2 in the forest strip. Section 4 was located on the right-bank watershed horizontal part of the Dubovy ravine drainage area, on which sudan grass grew from June 21 to September 18, 1957 and was ploughed fallow during the rest of the time.

As seen from Fig. 3 i, on all sections in 1956 and in 1957 there were periods of drenching the upper 1—1.5 m layer of the soil to a moisture exceeding the least moisture-holding capacity.

In the completely open drainage area (section 1) and in the forest strip (section 3) drenching of the 1 m soil layer was observed only in April-May. The duration of the period of drenching diminishes with the depth from the surface.

In sections situated on the fields between the strips (sections 2 and 4) the period during which the moisture of the upper soil layers equalled or exceeded the least moisture-holding capacity lasted almost half a year, beginning from January till May-July.

On examining fig 3 g (and 3 i) one can detect the effect of the nature of the plant cover on sections located on the fields between forest strips (sections 2 and 4).

Thus in 1956 when section 2 (fig. 3 g) was lying fallow, the soil moisture in the upper layers attained the value of the least moisture-holding capacity as early as the middle of September, and by the end of October a one-metre layer of soil was soaked through. In section 4 (fig. 3 i), which during this summer was under sudan grass, these manifestations were postponed respectively to the end of October and the end of November. The slight discharge of soil moisture on fallow is also confirmed by observations of 1957. In section 2 (fig. 3 g), sown to winter wheat, the soil moisture dropped below the value of the least moisture-holding capacity as early as the first half of May; whereas on the fallow field of section 4 (fig. 3 i) the soil moisture in the 0.10—1.0 m layer was at the least moisture-holding capacity value up to the middle of June.

From the period of July till October the moisture of the one-metre soil layer does not reach the value of the least moisture-holding capacity in any

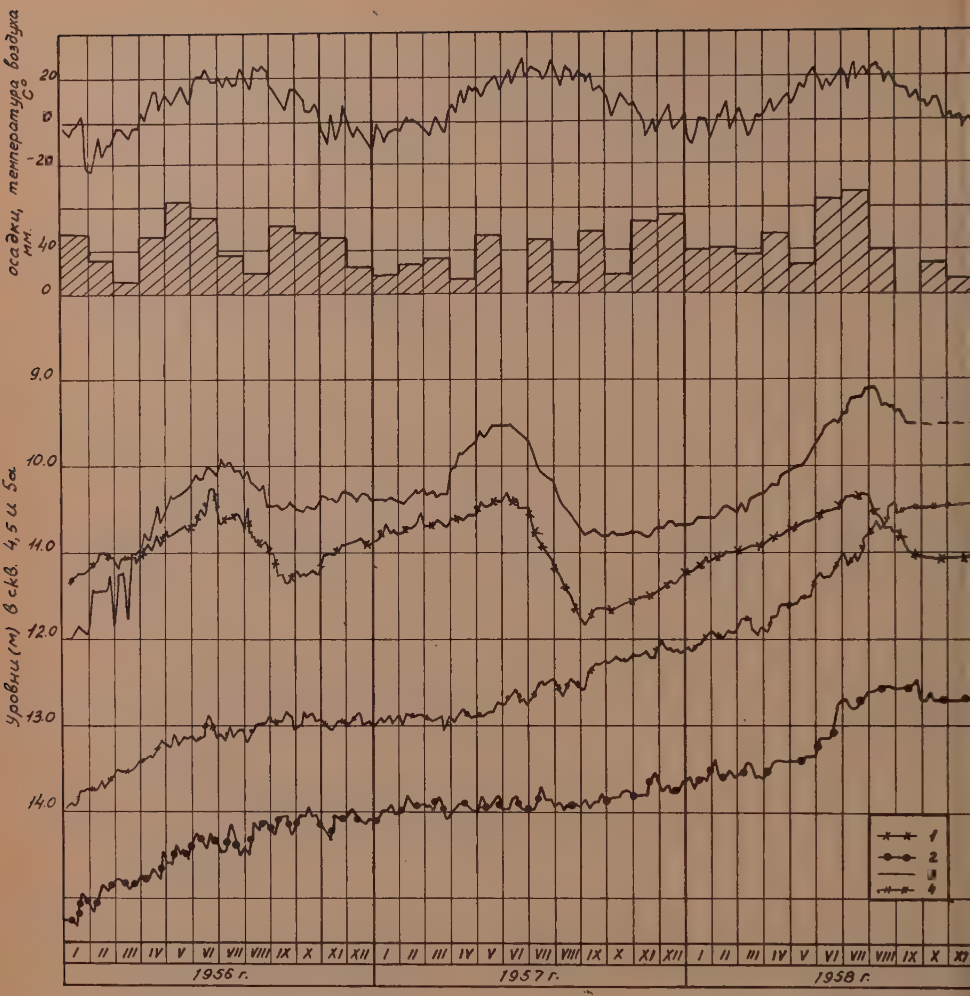


Fig. 5 Change in ground water levels in the vicinity of the Veliko-Anadol draining station.
1—Sukhoy ravine, borehole 5; 2—Sukhoy ravine, borehole 6 a; 3—Dubovy ravine, borehole 4

section. Rainwater is accumulated by the soil during this period and cannot percolate beyond the limits of the soil profile.

Thus, feeding of ground waters by water seeping through from the surface may be observed only during the winter-spring period. This is confirmed by the rise in the ground water level in all boreholes, observed annually during this period (fig. 5). The rise in the level that went on during July-August 1957 in boreholes 5 and 6a of Sukhoy ravine was evidently due to the continuing seepage of waters accumulated in the soil during the spring.

In the course of three years of observations (1956—1958) a rise in the ground water level occurred in the open drainage area which ceased only during the summer-autumn period. In the drainage area of the Dubovy ravine, however, where the boreholes were located in forest strips or near them, regular seasonal fluctuations were noted, typified by a distinct rise from March to June-July, followed by an abrupt fall terminating in September.

The explanation of these fluctuations in the ground water levels was given by G. N. Vysotsky (2). The intensified spring rise is due to waters percolating from the surface. In the forest strips the rise increases because of the formation of snowdrifts, and because of the water coming from the fields between the strips, which is intensely absorbed by the forest strip. The fall in the ground water levels due to moisture absorption by tree roots begins in June-July. This fall was called desuctive by G. N. Vysotsky.

From the moment of the termination of intense transpiration of trees, a slight rise in the ground water levels begins which may be accounted for by the flow of ground water from the fields adjoining the forest strips and called corrective.

The average ground water levels continually rose during the period under discussion. The rise in the average annual levels was also noted in borehole 4 located in a forest strip.

On examining the results of observations on the boreholes in the Sukhoy and Dubovy ravines (table 3 and fig. 5), it is seen that the ground waters occur several metres deeper in the field than under the forest strips. The compared boreholes, having orifice marks, are located in different parts of the drainage area. However, this does not affect the relationship between the ground water levels both in the field and under the forest strips. As a matter of fact, on comparing the ground water levels in the boreholes, located in the upper part of the drainage area, with orifice marks on Sukhoy ravine 246.9 (borehole 6a) and on Dubovy ravine 257.2 m (borehole 6), it is found that in this case too the level is 3 metres higher under the forest strip than in the field.

Thus, the data of the observations of the Veliko-Anadol draining station permit drawing the following conclusions:

1. the percolation of meteoric waters and the feeding of ground waters is observed on the territory of forest strips and open sections. It occurs during the winter-spring period;

2. under the forest strips the ground waters occur several metres higher than in the field, due to supplementary sources of moisture from retention of snow drifting from the woodless spaces, and to the absorption of the surface run-off from the adjoining fields;

3. the ground water level in the open drainage area rose almost continuously in the course of three years of observations (1956—1958). Regular seasonal fluctuations with a spring rise and an abrupt fall in the course of the summer period were observed in the forest strips and near them.

Let us sum up.

An analysis of the observations on the Black Forest, the Trostyanets forest range and in the forest strips in the Veliko-Anadol district, completely confirmed the conclusions of P. V. Ototsky (11) and G. N. Vysotsky (2) to the effect that ground waters lie deeper under the forest than in woodless sections, as well as G. N. Vysotsky's (2, 3, 4) conclusions as to the desiccating role of forest ranges in the steppe and forest-steppe districts of the Ukrainian

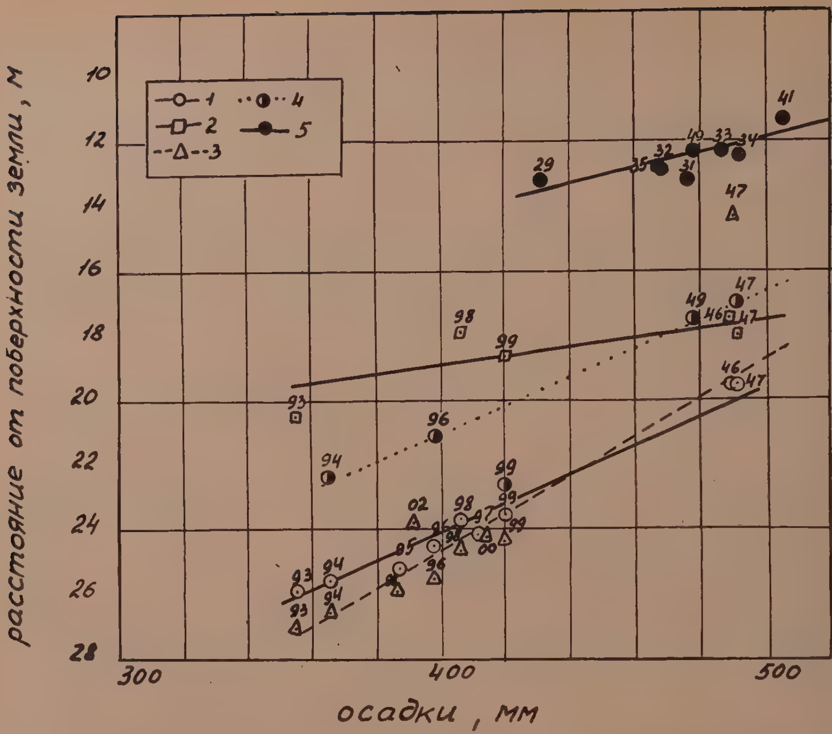


Fig. 6 Graph of dependence of average annual ground water levels on the average annual precipitation, computed by sliding decades in the Veliko-Anadol forest area.
1—in the nursery on the barrow; 2—railway well on the barrow; 3—forest strip-range 32; 4—railway well at division 58; 5—division 14. Two digit numbers on the graph denote the last two digits of the years of observation.

SSR and the favourable effect of forest strips on the soil moisture and ground water conditions.

The results of our study also agree with the data obtained by other authors who conducted observations in the three aforementioned districts (1, 5, 12-15, 17) and only the conclusions of I. M. Labunsky (7-10) sound a discordant note among the numerous researches devoted to this problem.

I. M. Labunsky asserts that in the vicinity of the Veliko-Anadol forest range the ground water level continually rises, which is due to the favourable effect of the forest on the replenishment of the ground waters both under the forest and in the adjoining area. The feeding of the ground waters occurs because of the influent character of the movement of moisture in the soils under the forest.

In A. I. Iroshnikov's paper (5) several arguments are advanced which cast doubt on I. N. Labunsky's conclusions.

The conclusions actually are erroneous. In addition to A. I. Iroshnikov's arguments the following points are to be considered in judging the validity of Labunsky's conclusions:

1. I. M. Labunsky finds confirmation of the influent nature of moisture movement in the soils in the observed rises of the ground water levels after abundant summer showers in 1946—1948. Observations on ground waters during the period were conducted on boreholes without tubing, drilled when taking samples for testing the moisture of the soils. Water formed on the trampled down space around the boreholes and on the trails during heavy showers may have flowed into the borehole and raised the ground water level; the walls of the borehole might also have caved in under such conditions.

2. I. M. Labunsky presents data on the rise in the ground water levels in populated spots directly adjoining the forest. The investigation conducted during the first half of January 1959 by one of the authors showed that the ground water level occurs at present close to the surface, not only in the forest but at a distance from it as well. In the village of Blagoveshchenskoye, mentioned several times by I. M. Labunsky, the ground water occurs in places at a depth of 1-2 m. However, ground water is found at the same depth in the villages of Volnovakha and Arsenyevo, in the city of Dokuchayevsk and in the vicinity of the station Dolya, points from three to several tens of kilometres distant from the forest and located on high watershed sections.

3. Comparing the ground water level in a number of boreholes during various years, I. M. Labunsky (9) explains the observed rises by the influence of the forest, asserting that in the course of a century "... no perceptible changes have occurred in the quantity of precipitations in the Donets Basin". Actually, however, the observed fluctuations in the ground water levels agree well with the changes in the precipitation taken over a period of many years.

Fig. 6 shows the connection between the average annual ground water levels taken from the cited paper (9) and the average annual precipitations (1) during the ten-year period preceding the given year. The average annual precipitations for 1949-1958 were computed, for instance, for the 1958 levels. An exception was made only for the 1893 levels, for which precipitations were computed for a nine-year period, since reliable data on precipitations are available for the Veliko-Anadol district from 1885 only.

The data presented in Fig. 6 show that under the conditions of Veliko-Anadol, there is a direct dependence between the change in precipitations and the ground water level of the following form

$$\triangle H = K \triangle X,$$

where $\triangle H$ is the change in level during the period in cm;

$\triangle X$ is the change in the average annual value of the precipitations for the decade preceding the beginning and end of the period;

K is a coefficient varying from 1-2 for the fourth division and railway well at the barrow to 5-6 for the forest strip and open section.

Thus, the rise in the ground water level established by I. M. Labunsky for the Veliko-Anadol forest by comparing the results of observations conducted in 1893-1900 and in 1948-1959 may be accounted for by the fact that during the second period the precipitations smoothed out during a decade proved to be about 100 mm higher than during the first period.

(1) The precipitations for 1892, 1945-1950 are taken from the observations of the Volnovakha hydrometeorological station; for 1893-1900, from the data of the meteorological station of Mariupol forestry No. 6; for 1920-1922, 1925-1926, from the data of the meteorological station of Mariupol forestry No. 9; for 1927-1935, averaged data of the Volnovakha and Mariupol forestry No. 9 stations. For 1951-1958, averaged data of the meteorological stations of Volnovakha, Veliko-Anadol forest, Dubovy ravine, Zeleny Gai. For other years, from the isohyet maps of annual precipitations compiled by N. I. Guk.

The tendency toward a rise in the water levels in the vicinity of the Veliko-Anadol draining station is also readily explained by the smoothed changes in precipitations. The average annual quantity of precipitations was 450 mm in 1945-1956, 447 mm in 1946-1957, and 477 mm in 1947-1958.

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RESULTS OF THE OPERATION OF THE EROSION MEASURING STATION AT KISNANA FOR THE YEARS 1956 TO 1958

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RÉSUMÉ

La station de mesure située au pied des versants méridionaux de la montagne Mátra (Fig. 1) a comme programme l'observation des processus de l'érosion de l'eau, pour aider la sylviculture dans ses travaux de la conservation du sol et de l'amélioration de l'économie de l'eau des sols forestiers dégradés.

La première partie expose la topographie, la structure géologique, le sol et le climat du bassin versant appartenant à la Station de mesure de l'érosion, elle caractérise les différents types de la couverture végétale (tableau 1), et donne une description des installations et de la technique de mesures de la station. La deuxième partie compare les résultats obtenus par le dépouillement des données de quelques précipitations caractéristiques avec les données hydrologiques et contient des propositions pour l'utilisation des résultats obtenus dans le domaine de la sylviculture.

La figure 2 montre la quantité mensuelle des précipitations pendant la période des observations ainsi que le coefficient d'écoulement de chaque mois. Le tableau 2. contient les données de la quantité annuelle des précipitations et les coefficients d'écoulement annuels.

Le tableau 3. présente l'analyse de quelques précipitations caractéristiques tenant compte des facteurs qui influencent l'écoulement superficiel, ainsi que le transport solide.

L'importance primordiale de l'intensité des précipitations et l'influence de l'état du sol sur l'écoulement et le transport solide sont montrés dans le tableau 4. La première partie du tableau montre le rôle de l'intensité de la précipitation l'état du sol ne variant pas (par le dépouillement des données de trois précipitations à quantité égale, mais d'intensité différente, d'une précipitation à grande quantité, mais d'intensité réduite et d'une précipitation à quantité réduite, mais de grande intensité). La deuxième partie donne la comparaison de trois précipitations à quantités et intensités presque égales, mais pour différents états du sol.

Les données des tableaux précédents se réfèrent à l'ensemble du bassin versant. Les résultats des observations relatives à l'effet de l'érosion sur les différents surfaces-types du bassin versant (tableau 1.) sont présentés dans les tableaux 5. et 6.

ZUSAMMENFASSUNG

Die Erosionsmeßstation (Abb. 1) in Kisnána, an den Füßen der Südhänge des Mátra-Gebirges, ist mit der Beobachtung der Wassererosionsvorgänge beauftragt, um der Forstwirtschaft bei den Bodenschutzarbeiten und bei der Verbesserung des Wasserhaushaltes degradierter Waldböden Hilfe leisten zu können.

Der erste Teil enthält die Beschreibung der Topographie, der geologischen Struktur, der Boden- und Klimaverhältnisse des Einzugsgebietes, der Ausstattung und der Meßtechnik der Station sowie die Kennzeichen der verschiedenen Typen der Vegetationsdecke (Tabelle 1). Der zweite Teil vergleicht die Ergebnisse der Bearbeitung einiger der meist charakteristischen Niederschläge mit den hydrometrischen Daten und enthält Vorschläge für die Anwendung der bisherigen Ergebnisse im forstlichen Fachgebiet.

Abb. 2 zeigt die monatlichen Niederschlagsmengen im Beobachtungszeitraum sowie die entsprechenden Abflußbeiwerte. In Tabelle 2 sind die jährlichen Niederschlags- und Abflußmengen angeführt.

Die Tabelle 3 veranschaulicht die Auswertung einiger der meist charak-

teristischen Niederschläge. Es sind alle Faktoren aufgezählt, die die Größe des Abflusses und der Schwemmstofführung beeinflussen.

Die in der Tabelle 4 zusammengefaßten Daten einiger Niederschläge zeigen, daß unter den Faktoren, die auf den Abfluß und auf die Schwemmstofführung auswirken, die Intensität der Niederschläge die erste Rolle spielt, doch ist auch der Zustand des Bodens von großer Bedeutung. Die erste Hälfte der Tabelle zeigt die Rolle der Intensität der Niederschläge bei gleichem Bodenzustand (durch die Bearbeitung dreier gleich großen Niederschläge mit verschiedener Intensität sowie eines großen, aber nicht intensiven und eines kleinen, aber intensiven Niederschlages). Die zweite Hälfte der Tabelle gibt die Vergleichung dreier beinahe gleich großen und intensiven Niederschläge bei verschiedenem Bodenzustand.

Die Daten der vorangehenden Tabellen beziehen sich auf das in Flächentypen geteilte ganze Einzugsgebiet (Tabelle 1). Die Ergebnisse der Beobachtungen der Erosionswirkung auf die Flächentypen sind in den Tabellen 5 und 6 zusammengefaßt.

The object of the Erosion Measuring Station, established in the years 1954 and 1955, is to investigate and determine the processes of erosion by the action of water and all the factors having influence over them; to determine the sequence in importance of these processes. A further aim is to bring about an improvement in the water economy of the impaired forest stands and in the condition of the soil by turning to full use the observations made.

I. The Erosion Measuring Station

The Experiment Station is situated on the outskirts of the village of Kisnána, at the southern and south-eastern foot of the Mátra mountain, in the catchment area of the Tarnoca brook. The area constitutes the head of a valley spreading out in the shape of a fan. The precipitation is run off by four ravines of medium depth which unite in front of the main valley and by several other smaller ravines *(Fig. 1)*.

On the catchment area there is no permanent or seasonal spring or water course. (Except that one of the ravines has a trickling flow early in the spring and in the autumn, making about 5 to 8 m^3 in 24 hours.)

The Station's area is 7,44 hectares. The part controlled by the measuring weir is as large as 4,88 ha. It is exposed mostly in a western, south-western and southern direction while its minor part lies to the south-east and north-east.

Its altitude above sea-level rises from 132 to 208 meters. The slope of the surface is between 0,5 and 2 degrees in the vicinity of the divides and varies from 5 to 22 degrees on the slopes.

The length of the slopes varies between 20 and 180 meters, most of them being 80 to 100 meters long. The most distant point of the catchment area is 310 meters away from the weir.

Throughout the whole area of the catchment, *the baserock* is riolite tuff, embedded into which there are pieces of andesite of various size. The rock is little fissured but it is permeable. It disintegrates very easily. On areas left uncovered by soil, the base rocks might disintegrate to a depth of 2 centimeters a year. At the south-eastern part of the catchment, above the base-rock, there is a thick layer of gravel.

The soil originates from the disintegration of sour, volcanic rock. In most places we find the remnants only of the once sour, brown forest-soil, fallen off and reduced to the state of defective soil. There are, however,

plenty of pieces of land in the catchment where the soil is practically gone or has deteriorated to the base rock. The heaviness of the soil varies from the heavy loam to clay, it is slightly sour or neutral (5,2 to 7 pH), its humus content is small. Its permeability is very low owing to its cledginess and consequent to immoderate pasturing. These factors set aside, water-economy is badly influenced by the exposure of the catchment and by the steepness of the surface.

Owing to pasturing, it is now difficult to determine the primordial flora and the former types of forests. Prior to the present deteriorated condition, part of the areas is likely to have belonged to the downy oak type, with very dry neutral soil, and another to the dry, slightly sour blaze-oak forest

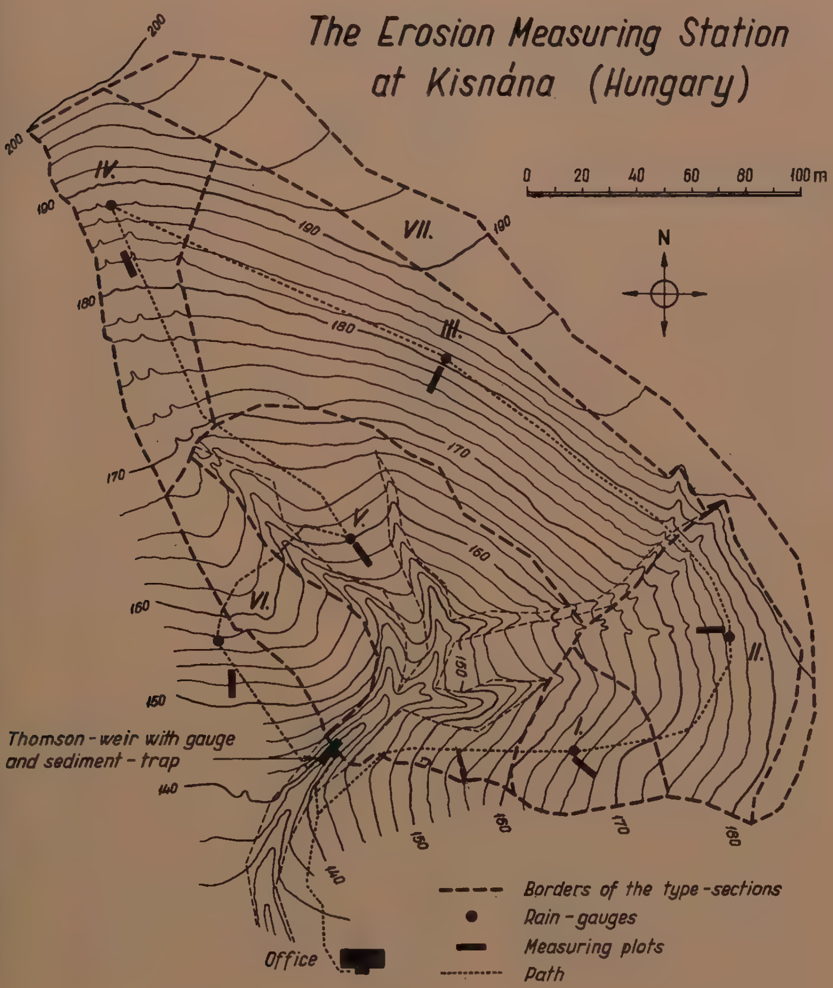

Figure 1.

TABLE 1

DESCRIPTION OF THE TYPE-SECTIONS

Number	Description	Exposure	Slope degree	Grass-level: Ratio of cover	Grass-level: Genera	Sort of wood: Ratio of cover	Sort of wood: Genera	Bushwood: Ratio of cover	Bushwood: Genera	Area m²
I.	*Forest getting barren.* Brown-forest soil; light loam, permeable, mixed with gravel, moderately sour.	N to NW	14 to 16	0,9	Thymus. Genista pilosa. Festuca pseudovina. Poa nemoralis. Agrostis tennuis.	0,4 to 0,5	Pinus nigra. Fraxinus ornus 3 to 4 m high Fraxinus ornus	0,1	Fraxinus ornus. Rose. One m high.	2 116
	Measuring plot		15,5							
II.	*Strewn bushwood.* Shallow, heavy moderately sour loam divided by small ravines. Brown forest soil. Here and there skeleton soil, laid to waste to base-rock irregularly. Permeability bad.	W to SW	14 to 16	0,6	Thymus. Genista pilosa. Andropogon.	1-1 wood	Fraxinus ornus. Robinia pseudacacia. Quercus cerris. Quercus petrea. 3 to 4 m high	0,4 to 0,5	Fraxinus ornus. Quercus cerris and Robinia pseudacacia sprout. 1 to 2 m. Hawthorn. Blackthorn or Rose.	5 440
	Measuring plot		14,5							
III.	*Strewn wooded bushy grassland.* Moderately sour, fissuring, heavy loam, brown forest soil, bad water economy, skeleton-soil in patches.	SW to S	18 to 22	0,9	Andropogon. Festuca sulcata. Poa nemoralis. Agrostis tennuis.	0,1 to 0,4	Robinia pseudacacia. Quercus cerris. 3 to 4 m high	0,2 to 0,6	Blackthorn. Hawthorn. Rose. Quercus cerris and Robinia pseudacacia sprout. Rose, Hawthorn.	12 718
	Measuring plot		20,5	0,8		0,2				

The type-section's

Number	Description	Exposure	Slope	Grass-level		Sort of wood		Bushwood		Area
			degree	Ratio of cover	Genera	Ratio of cover	Genera	Ratio of cover	Genera	m²
IV.	*Mountain-grassy pasture.* Moderately sour, heavy loam surface, stony, fissuring, more or less closed. Part of it devastated to the base rock.	S to SE	6 to 15	0,6	Lolium perenne. Festuca pseudovina. Festuca sulcata. Poa pratensis	0,1 to 0,2	Robinia pseudacacia.	Many	Blackthorn. Hawthorn. Rose.	6 280
	Measuring plot		13	0,8						
V.	*Acacia forest.* Moderately sour, heavy loam, brown forest soil.	NW to SE	8 to 12	0,5	Bromus. Poa nemoralis Agrostis tennuis. Dactylis glomerata	0,7	Robinia pseudacacia. Sporadically Quercus cerris.	0,3	Robinia pseudacacia sprout. Hawthorn. Blackthorn, Privet, Blackberry.	13 416
	Measuring plot		10							
VI.	*Area devastated to the base-rock.* Divided by 0,5 to 0,8 m deep ravines. Here and there some accumulation of soil.	SE	5 to 20		Poa scabra. Festuca sulcata.					1 283
	Measuring plot	S	6							
VII.	*Level tract of pasture.* Loam heavily densed on the surface with deep fissures.	S to SE	0,3	0,9	Lolium perenne. Festuca pseudovina. Poa pratensis.					7 515

type line. *Table 1* contains a full description of the types of forests and the vegetation as they are now.

Because of its situation, *the climate* is warm to a marked degree. It is a closed kettle, open to the south only. North and north-western winds, humid and cool air with moisture are held up by the main ridge of the Mátra mountain occupying a north to north-western position whereas it is entirely open to the dry, warm air from the Hungarian Plain. Apart from the virtues of its soil, it is the warmth of the climate that makes the southern region of the Mátra so eminently suitable for the growing of grapes and fruit. At the same time, the steep sides of the mountain are dry and this makes a renewal of the vegetation more difficult. The normal annual temperature is 10° C.

Rainfall is scarce. The average for the past 40 years has been 538 millimeters, from this 312 millimeters fallen during the growing season. The monthly averages vary from 26-28 mm (in January and February) to 63 mm (in June). The average for the three year period of our investigations was 574,1 mm, 350 mm of them being in the growing season.

On the borders of the area appointed for measuring purposes, there have ditches been made to prevent inflow and flowing away at places where it appeared necessary. We had the whole area divided into seven (I-VII) type-sections according to the variety of the cover of the soil to be able to determine the run-off and the effect of erosion on every type of soil.

The shape and relief of the catchment area and its types of sections may be seen from *fig. 1* and the description of latters is given in *Table 1*.

Equipment of the Station

For climatic observations a first-class meteorological station was installed where a self recording rain-gauge serves to measure the intensity of rainfall. The average depth of precipitation over the area is ascertained on the basis of the data of 7 standard rain-gauges set up on each of the type-sections.

For the purpose of measuring run-off from the catchment area a Thomson weir was installed with a stilling box of the size of 1,50 by 1,70 and 7 meters long serving also to measure the quantity of eroded material. The head on the weir is recorded by an automatic gauge placed in a measuring shaft and connected with the stilling box.

We obtain the quantity of the suspended silt from a series of water samples taken during the flood waves. The quantity of the rolled material can be determined by computing the volume retained in the stilling box. In order to determine the run-off and the quantity of eroded material for every one of the type-sections, we have stuck and delimited measuring plots of the size of 2 x 10 meters each, on type sections I to VI (excepting section VII which almost horizontal). At the lower end of everyone of these plots the run-off and the eroded silt is taken up in a shaft of the size of 2 cubic meters and weighed whereas the quantity of the precipitation is measured by a standard rain-gauge set up in each of the type-sections.

II. Measurements and data elaborated

In the course of the past three water years (as from November 1, 1955, to December 31, 1958) we have collected and elaborated all the data which

effect, directly or indirectly, the run-off and the sediment transport. Besides precipitation, its amount, duration, and intensity, attention was given to the temperature of the air and of the soil, the duration of the sunshine, and the wind velocity. All these have an influence on the run-off and the erosion and give us a good idea of the condition in which the soil had been before and during precipitation.

Figure 2 records monthly precipitations of the three water years, in millimeters, and run-offs in term of the percentage of precipitation. This diagram reveals greatest monthly run-off coefficients to be 57,0 p.c. in March 1956, 51,6 p.c. in April 1958 and 29,9 p.c. in February 1957. The frozen soil, the wet soil-surface and melting of snow combined with rain had contributed to the high amount of run-off.

It should, however, be noted that the run-off measured was produced not merely by the precipitation fallen in that month but also by the melting of snow and ice that had accumulated in the preceding months.

The highest monthly amount of run-off without snow melting was 23,2 p.c., produced in June 1958, an extraordinary wet months with a precipitation of 191,4 mm.

In *Table 2* we have recorded annual surface run-off during each of the water-years.

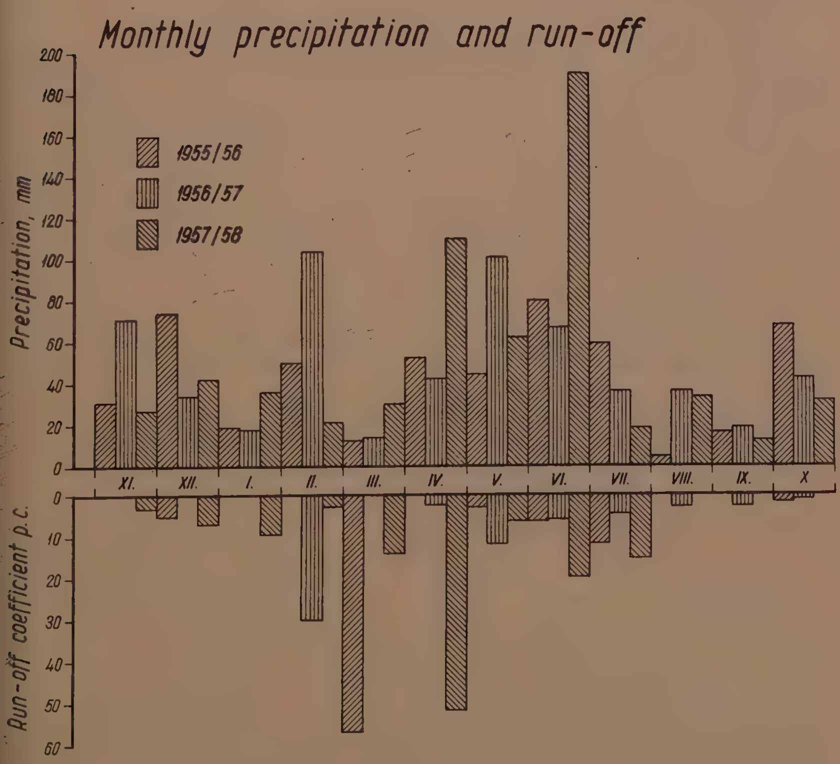

Figure 2.

TABLE 2

Precipitation and run-off during the years 1955/56 to 1957/58

Water year	Precipitation		Run-off	
	depth mm	total volume m^3	total m^3	in p. c. of precipitation
1955/56	523,8	25,534	934	0,04
1956/57	590,8	28,686	2005	0,07
1957/58	607,9	30,077	5769	0,19
Triennial average	574,1	28,099	2899	0,10

For the forestries in working out the plans to combat erosion and to improve the water economy, it is not enough to know the run-off coefficients in respect of years and months. Before everything, the maximum of run-off *that may be produced by different sorts of precipitation*, must be known. Therefore, we have worked out the data covering days with precipitation such as had—as a consequence—surface run-off.

Table 3 contains, a survey of these data grouped periodically.

Table 4 contains a few interesting observation concerning sediment transport. This statement deals with the effect of the intensity of precipitation and the soil condition on the run-off and the movement of silt. In the first part of it we assume soil conditions to be the same and we contrast the quantity of surface run-off and the amount of silt following three storms in 1957, almost equal in quantity but different in intensity, with a rainfall in 1958 of great volume, minor intensity and another precipitation small but very intense—to show what the intensity of precipitation really means.

It may be easily seen that the quantity of the run-off grows with the intensity of the precipitation and as the quantity of the run-off increases so goes up the quantity of the silt on move. A comparison of the two precipitations of 1958 likewise points to this that the intensity of precipitation is primarily responsible for processes of water erosion.

In the second part of the statement comparison is made of the run-off and the movement of silt, following precipitation of about equal quantity and intensity, *the condition of the soils being, however, not the same*. The object of this is to call attention to the significance of the condition of the soil when considering the run-off and the movement of the silt. The statement shows that during a prolonged period, the precipitation fallen was almost equal in quantity, low in intensity and yet they differed very considerably, as far as run-off and the movement of silt was concerned. On differences in the run-off, this is to be ascribed to the very different condition of the soil as noted in the column for remarks. As far as it concerns the volume of silt, the quantity of disintegrated matter present on the surface on the occasion of the precipitation plays its part too.

The data supplied so far cover the whole area of the catchment. The aims, however, set by our forest management demand that the erosional processes should be investigated for the various types of forests too. Therefore, inside the catchment area, on the type-sections different for their vege-

tation-cover—but on six only—measuring was carried out too in order to know the effects of the effects of the different sections as components of the resultant obtained for the whole catchment area. *Table 5* contains some of the results of these observations.

As said above, we have measuring plots on six of our type-sections only. (We have none on the seventh which is almost horizontal). For this reason we could compare the measuring results on the catchment with the results of the sections (components) by supplementing the measuring results with the estimated run-off of type-section VII. As section VII has a small incline only, our estimate is not likely to be inaccurate to any great extent.

The comparison made by us has produced interesting results and they are worthy of being investigated. For 1956/57 the weighted sum of the run-offs from the type-sections was equal to the amount of the run-off measured on the whole area, the surface run-off of type-section VII being an estimated figure, whereas for 1957/58 it was 70 p. c. only. The difference must be ascribed to the length of the slope. Proof that the length of the slope is responsible for the diminution of the run-off, can be furnished if the sum of amounts of run-offs obtained on the measuring plots, each being 10 meter long, and on being converted to the type-sections, is compared with the value of run-off measured at the Thomson weir. *It appears that from the precipitation yielding little run-off, we obtain always a lower amount of run-off at the weir than the sum of the run-offs calculated for the type-sections on the basis of the volumes of water retained by the shafts. On the other hand, given a precipitation with a higher run-off, it was for the whole catchment area that higher measuring results were obtained.*

In the year 1957/58, the total run-off measured was more than the double of that for the previous year. It can therefore be appreciated why the weighted sum of run-offs measured in that year on the six plots was smaller than the run-off measured at the Thomson weir.

If our experience as referred to before holds good, this we intend to test in the future by means of plots of a length of 20 and 40 meters respectively.

Results on the run-offs from the type-sections have already been made use of in the preservation of the soil. These tabular statements should convince us that plantations we are going to have for reducing erosion, must be preceded by a *preparation of the soil* making it capable of retaining precipitation water, over and above the natural water retention by each of the type-sections.

The results of our observations can also prove that there is a close relationship between the association of plants, the development of types of forests and the water economy of the soil. They also can facilitate the selection of the right sorts of trees for artificial forest-cultures and indicate the way their composition should be made up. They also may contribute to the rearing of more fertile stocks.

When comparing the quantity of silt weighed at the measuring plots of the type-sections with that collected at the Thomson weir, we again find that the differences are great. This, naturally, is to be ascribed to the length of the slope, its form (normal, convex or concave) and in connection with these to the greater quantity of water and its greater power to entrain silt. The longer plots we said we were going to have for measuring purposes, should enable us to have more satisfactorily data at our disposal. We should also point out that the major part of the silt comes from the ravines developed soon i. e. from the natural water courses. In these, according to the estimate

TABLE 3

EVALUATION

of a few characteristic precipitations fallen in the water years 1956/57 and 1957/58, in the summer and autumn and in the snow-melting season

Date		Precipitation				Total run-off
		Depth	Duration	Inten-sity	Total volume	
		mm	hours	mm/hour	m³	m³
1957.	II. 13.	18,2	8	2,3	883	
	14.	11,7	8	1,5	568	610
	15.	18,3	13	1,3	890	385
	17.	7,1	3	2,4	326	35
	18.	4,7	4	1,2	218	20,8
1958.	III. 23.	6,4	4	1,6	312	
	24.	0,9	3	0,3	44	46
	25.	Melting				
	26.	Melting				
	27.	0,3	3	0,1	14,6	50
	28.	1,2	6	0,2	58,5	
	IV. 4.	23,0	10,3	2,2	1127	
	5.	7,2	6	1,2	354	1015
	6.	16,0	10	1,6	785	
1957.	V. 19.	17,5	1,5	11,7	862	74,5
	VI. 8.	1,9	1,7	1,1		
		19,9	0,3	59,7	1070	138,6
	VII. 11.	20,5	3	7	999,6	36,6
1958.	V. 16.	15,0	0,12	75	836,8	92,6
		2,6	0,8	3,3		
	VI. 11.	57,8	24	2,4	2972	
	12.	53,7	24	2,3	2726	1423,2
	VII. 3.	12,1	2,10	6	602,5	116,9
	VIII. 16.	11,7	4	3	572	7
1957.	IX. 14.	11,1	0,5	22,2	534,1	13,9
	X. 22.	38,0	16,1	2,4	1845,8	26,9
1958.	X. 16.	10,0	1,6	6,3	—	5,0

TABLE 3

Run-off coeffi-cient	Silt removed			Remarks
	Sus-pended	Rolled	Total	
p.c.		m^3		
42 43,2 9,3 9,6	0,22	1,33	1,55	Frozen surface of soil melted. Soaked. Snow melted away between the 10th and 12th.
13				Soil frozen. Thaw setting in on the 24th. Snow cover continuous and 6 cm deep. On the 25th patches only.
70				Thawing strong. Snow in patches. No snow on the 28th. Soil frozen.
43,8	5,82	2,96	8,78	Soil-surface soaked, can hardly absorb water
11,6	0,41	2,18	2,59	Soil dry, fissured
12,9	1,12	4,79	5,91	Ditto
3,7	0,33	0,89	1,22	Ditto
11	13,9	6,53	20,43	Soil surface drying up
24,8	0,78	3,78	4,56	Dry, indurated before rain. Remained fissured after it.
18,5	0,19	0,62	0,81	Dry. Fissured
0,7	0,16	—	0,16	Ditto
2,6	0,25	0,41	0,66	Soil dry, fissured
1,5	0,05	—	0,05	Ditto
5,0	0,4	—	0,4	Dry, fissured

TABLE 4

RUN OFF PRODUCED BY PRECIPITATIONS OF DIFFERENT INTENSITY AND IDENTICAL QUANTITY

and different intensity and different quantity respectively and sediment transport, soil conditions being different likewise

Date	Precipitation				Run-off		Sediment transport			Soil condition
	Depth	Total volume	Duration	Intensity	total	p.c.	Suspended	rolled on	total	
	mm	m^3	hour	mm/min	m^3		m^3			
1957. VIII. 28.	22,4	1094,2	7,2	0,052	11,8	1,1	0,18	—	0,18	Dry
VII. 11.	20,5	999,6	3,0	0,114	36,6	3,7	0,33	0,89	1,22	Ditto
VI. 8.	21,8	1070,4	0,75	0,545	138,6	12,9	1,12	4,79	5,91	Ditto
1958. VI. 11.-13.	113,5	5598,1	48	0,039	1423,2	24,8	0,78	3,78	4,56	Dry. Surface wet during the rain.
V. 16.	15 2,6	836,8	0,2 0,8	1,25 0,054	92,6	11,1	13,9	6,53	20,43	Dry
1957. X. 22.	38,0	1845,8	16,1	0,039	26,9	1,5	—	0,05	0,05	Quite dry
V. 5.-8.	41,8	2043,6	36,1	0,019	367,5	32,1	0,12	0,36	0,48	Halfwet
1958. IV. 4.-7.	46,2	2266,0	26,3	0,029	1015,0	43,8	5,82	2,96	8,78	Wet. Thawed
IV. 16.-17.	43,1	2344,0	39,5	0,018	1648	74,4	0,73	4,24	4,97	Soaked. Very wet

accepted in hydrology, the water rushes down with a ten times greater velocity than on the sides. Accordingly, its tractive force exerted on the bottom and the sides of the channel can be the manifold of the impairment inflicted on the soil-surface of the slopes.

At the Thomson weir, in the year 1956/57, we altogether recorded 13,24 m³ and 3,8 m³ in the shafts at the plots. In 1957/58, the corresponding figures were 54,89 m³ for the weir and 8,62 m³ for the plots. *Table 6* shows the weight of the silt weighed on each of the plots, after some precipitations. *It is clear that 99,5 p. c. of the silt comes from uncovered areas. Therefore, the first and foremost business of the forestries is to see to it that soil no longer remains without a cover.*

The measurement figures contained in tables 5 and 6 prove that the best means of reducing run-off and stopping the erosion is to have the soil properly covered by a forest. While making our observations, we found that the surface run-off *on the type-sections with forest-cover* was 4 p. c., on an average and had never risen higher than 20 p. c., except the period of melting of snow and there was no silt from that region. On pastures and grassland surface run-off has already shown a considerable increase on days with precipitation. Its volume averaged 15 p. c. of the precipitation but the maximum on days without melting came as high as 50 p. c. Even so, the sediment transport made an insignificant figure (0,1 p. c.). As a contrast to this, the average of the run-off on uncovered or devastated areas came as high as 70 p. c. and the silt moved on came to, as mentioned before, 99,5 p. c.

TABLE 6

Quantity of silt removed from the various type-sections

Water year	Date	Quantity of silt in m³ removed from the type-section						
		I.	II.	III.	IV.	V.	VI.	Total m³
1956/57	V. 19–21.	—	—	—	—	—	1,922	1,9220
	VII. 8.	—	0,0016	—	0,0012	—	1,281	1,2838
	VII. 11.	—	0,0100	—	—	—	0,591	0,6010
Sum:		—	0,0116	—	0,0012	—	3,794	3,8068
1957/58	IV. 16–18.	—	—	—	—	—	1,2809	1,2800
	V. 16.	—	0,014	0,019	—	—	6,4226	6,4556
	V. 24.	—	0,007	—	—	—	0,0017	0,0087
	V. 29	—	0,010	0,016	0,005	—	0,0003	0,0313
	VI. 11.–13.	—	0,057	0,006	0,052	—	0,3900	0,5050
	VI. 29.	—	0,0014	—	—	—	0,0370	0,0384
	VII. 3.	—	0,006	0,003	0,005	—	0,2350	0,2496
	VIII. 16.	—	—	—	—	—	0,0260	0,0260
	X. 16.	—	—	—	—	—	0,0300	0,0300
Sum:		—	0,0954	0,044	0,062	—	8,4226	8,6240

TABLE 5

EVALUATION OF CE

measured during the water years of

Date of the precipit- ation	Type-section I.				Type-section II.				Type-section II		
	Precipit- ation		Run-off		Precipit- ation		Run-off		Precipit- ation		Run
	mm	m³	m³	p.c.	mm	m³	m³	p.c.	mm	m³	m³
1957. II. 13., 14., 15.	45,6	96,5	0,6	0,6	48,6	262,2	24,0	9,2	47,5	608,1	127,4
II. 16., 17., 18.	12,0	25,4	—	—	12,7	67,5	7,6	11,3	11,4	151,2	30,5
1958. IV. 4., 5., 6., 7.	45,0	92,2	—	—	47,1	256,2	266,6	104,0	47,1	599,0	216,2
1957. V. 19., 21.	22,1	46,8	—	—	22,4	126,3	22,3	17,7	20,0	255,4	—
VI. 8.	21,3	45,0	—	—	23,0	124,2	46,9	37,8	22,6	282,9	15,2
VII. 11.	19,2	40,6	—	—	20,9	113,7	30,0	26,4	20,6	265,2	13,9
VIII. 28.	22,1	46,8	—	—	21,5	121,1	27,7	22,8	23,6	292,5	13,9
1958. V. 16.	19,1	40,4	2,1	5,2	19,8	107,7	19,0	17,6	15,7	199,7	31,8
VI. 11., 12.	116,2	245,9	2,1	0,9	122,8	668,0	405,3	60,6	118,8	1510,9	248,0
VII. 3.	12,2	25,8	—	—	12,7	69,1	21,8	31,6	12,2	155,1	19,0
VIII. 16.	12,2	25,8	—	—	12,1	65,8	19,9	30,3	11,6	147,5	12,7
1957. IX. 14.	11,0	23,3	—	—	11,1	60,9	27,2	44,7	11,1	140,8	16,5
X. 22., 23.	42,2	87,2	—	—	41,7	224,0	19,0	8,5	40,4	520,7	12,7
1958. X. 16.	10,0	21,2	—	—	10,2	55,5	—	—	10,5	133,5	—

At the erosion measuring station, it is planned to *carry out the observations in three stages*. The first extends over 4 years and the other two have 3 years each. In the first section, the observations are now made in maintaining the initial conditions on the catchment area. The second stage begins in November this year with the felling of trees and continues on cut down and grazed land, close attention being given to the increasing erosional effects produced. The work is to be continued and brought to completion in November 1963, by preparing the soil and the planting of trees.

The object of the observations to be made in these periods is to frame rules for guidance in our actions and these might be made use of at places of the same conditions. The investigations carried on so far have not yet produced such results but we now possess many valuable data and these can be used in proving the correctness of several processes and assumptions. Attention was invited to these when introducing our tabular statements. For instance, run-off coefficient, the role of forest-cover, etc.

.RACTERISTIC RUN-OFFS

1957/58 on the type-sections

Type-section IV.				Type-section V.				Type-section VI.			
ecipit- ation		Run-off		Precipit- ation		Run-off		Precipit- ation		Run-off	
1	m³	m³	p.c.	mm	m³	m³	p.c.	mm	m³	m³	p.c.
7	298,7	285,0	95,5	49,2	660,0	53,7	8,2	47,4	61,4	87,2	142,0
1	75,9	75,3	99,3	13,3	178,4	13,4	7,5	12,6	15,8	25,0	158,3
7	305,8	78,5	25,6	44,7	599,7	13,4	2,2	45,3	58,1	39,1	67,3
5	150,3	40,8	27,2	21,1	283,1	—	—	24,6	30,9	18,6	60,2
8	134,7	14,5	10,8	20,0	268,3	43,6	16,2	21,6	27,6	16,8	60,9
,1	126,9	—	—	19,5	251,6	—	—	20,7	26,9	18,6	69,2
,5	135,0	—	—	20,2	271,0	—	—	23,8	30,1	17,3	57,5
,0	100,5	50,0	49,7	14,2	190,0	—	—	18,4	23,6	19,9	84,5
,8	790,0	103,6	13,1	99,6	1336,2	80,5	6,0	123,3	152,2	101,3	66,5
,9	81,0	22,0	27,2	12,0	161,0	—	—	12,7	16,3	9,6	58,9
,5	78,5	9,4	12,0	11,5	154,3	—	—	12,6	15,9	8,4	52,8
,2	10,3	—	—	11,0	147,6	—	—	11,3	14,7	9,9	66,3
,5	154	—	—	41,0	550,0	—	—	40,8	52,3	35,0	66,8
,4	64,1	—	—	10,1	135,5	—	—	10,8	13,9	7,4	53,2

A CONTRIBUTION TO ELUCIDATION OF THE EVAPOTRANSPIRATION OF FOREST STANDS ON CLAYEY SOILS WITH A HIGH GROUNDWATER-TABLE

by **H. HOLSTENER-JØRGENSEN**
The Danish Forest Experiment Station

On level ground with a clayey soil and a high water-table it seems possible to calculate the evapotranspiration on the basis of simple measurements.

At The Danish Forest Experiment Station periodical measurements of the depth to the water-table below various tree species and various types of stands have been carried out during recent years. The depth to the water-table is measured in bored wells with a diameter of 10 cm.

Table 1 shows the water-table fluctuations from April 1, 1956, to March 31, 1957, in a 65 years old beech stand (*Holstener-Jørgensen* 1959 a). The figures represent the monthly mean-values of the measured distances to the water-table. It appears, that the water-table reaches its highest level outside the growing season. As soon as the stand begins to consume water, the water-table falls. The lowest water-table (depth: 135 cm) seems to be very nearly constant from year to year and lies 20—30 cm below the deepest roots of the stand (established depth of roots : 115 cm). When the trees cease to consume water, the soil is gradually saturated with water from above, and after saturation the water-table rises again.

TABLE 1

Water-table fluctuations in a beech stand from April 1, 1956, to March 31, 1957

Month	Mean depth to water-table cm
Apr. 1956	26
May —	42
June —	85
July —	114
Aug. —	125
Sept. —	106
Oct. —	117
Nov. —	87
Dec. —	30
Jan. 1957	31
Febr. —	7
March —	30

From an examination in detail of the individual measurements on which *Table 1* is based, it appears, that when the water-table is high in wintertime, it shows a continuous fluctuation. Immediately after rainfall or melting

TABLE 2

Survey of pores > 30 μ and clay content
Mean-values for two soil pits in the beech stand

Depth cm	Volume-% pores > 30 μ	Weight-% clay
0—5	30.9	23.7
10	16.8	23.0
20	8.3	21.2
30	6.2	24.3
40	6.9	—
50	7.5	—
60	7.0	21.9
70	6.8	—
80	6.4	—
90	5.7	—
100	4.6	20.7
110	4.3	—
120	4.2	—
130	3.8	—

of snow it rises, to fall again to a certain depth in a short while. We have called this depth, which is well-defined for the separate locality, the "*highest stable water-table*". In the above mentioned beech stand the measurements show the "*highest stable water-table*" to be in the depth of 30 cm.

Table 2 shows the content of macropores at various depths in the beech stand. The figures indicate, that the content of macropores is highest in the top-soil and low in the deeper layers. The high content of macropores in the top-soil permits a quick lateral flow of water to the ditches in the area, and "*highest stable water-table*" coincides with the depth in the soil, in which the content of macropores is low. In this connexion it may be mentioned, that drainage experiments in localities with a similar type of soil show, that 150 cm deep ditches are unable to lower the water-table below "*highest stable water-table*" at a distance of more than 4—5 m from the ditch (unpublished data).

The observations just mentioned, in connexion with the fact that within a stand the ground-water falls to very nearly the same depth every year, make it probably justifiable to consider areas of this type as closed basins, only subject to drainage when the ground-water rises above the "*highest stable water-table*".

Because rainfall never rises the water-table to the "highest stable water-table" during the growing season under our climatic conditions, it follows that—
The evapotranspiration = the total precipitation in the period from the moment when, in Spring, the descending ground-water passes the "highest stable water-table" until, after the growing season, it again reaches the "highest stable water-table".

So far, this extremely simple method for the determination of the evapotranspiration has shown results, which seem logically indisputable.

TABLE 3

Calculated evapotranspiration in mm rainfall for a beech stand (65 years old) and a Norway-spruce stand (45 years old)

Year	Beech		Norway-spruce	
	Calculation period	mm	Calculation period	mm
1956	Apr. 19—Dec. 14	481	Apr. 15—Dec. 13	471
1957	Apr. 10—Dec. 28	417	Febr. 28—Dec. 28	469
Mean	(Apr. 15—Dec. 21)	449	(March 23—Dec. 21)	470

Table 3 shows the calculated consumption of water in two periods of growth in the above-mentioned beech stand and a neighbouring, 45 years old Norway-spruce stand (*Holstener-Jørgensen* 1959 a). While in 1956 their water-consumption was very nearly of the same size, the Norway-spruce stand in 1957 had a water-consumption which surpassed that of the beech stand by 50 mm. This is due to the fact, that the late winter of 1956-57 was extraordinarily mild, so that the Norway-spruce stand (evergreen) has begun its transpiration at a very early date (Febr. 28). Such an early transpiration is well-known from phytophysiological investigations.

Table 4 shows how clear-cutting and shelterwood-cutting displace the date at which the "*highest stable water-table*" is reached after the growing season (*Holstener-Jørgensen* 1959 b). It appears, that an extreme opening

TABLE 4

Date of "highest stable water-table" in autumn	Control	Shelterwood-cut in early spring 1957	Clear-cut in early spring 1957
1956	Dec. 8	Dec. 15	Dec. 21
1957	Dec. 28	Oct. 15	Sept. 5

of the crown canopy and a consequent reduction of the transpiring leaf-surface results in a reduced water-consumption (about 140 mm). Clear-cutting and the change-over to clear-cut flora reduces the water-consumption even more (about 220 mm).

We suggest, that measuring of the fluctuations of the water-table should be carried out more extensively. Our observations show, that there is reason for assuming that in many cases such measurings would provide valuable information concerning the water-consumption of forest-tree stands. Furthermore it would be possible to collect material for the elucidation of how interferences in the silvicultural system (selection of tree species, felling, etc.) may influence the water-consumption.

The localities described may be considered as lysimeters in a big scale under quite natural conditions, permitting experiments, which could never be carried through under the conditions provided by a laboratory.

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METHODS OF STUDYING THE DEPENDENCE OF RIVER RUNOFF ON THE FOREST COVERAGE OF ITS BASIN

by P. F. F. IDSON

SUMMARY

1. The controversy concerning the effect of the forest coverage of a basin on the river runoff is due mainly to the faultiness of the methods used earlier for comparing the percentage forest coverage and the magnitude of river runoff. At present a great deal of facts obtained by Hydrometeorological observations have been accumulated in the USSR and in other countries, making it possible to clear up this question quite satisfactorily. However, in specific application to problems of forest hydrology not only the forest coverage has to be analysed, but the separate influence of all the main physico-geographical factors as well, and possible methods of objectively assessing the role of the latter in forming the runoff in the basins under study must be outlined. A procedure worked out on the basis of such an analysis is accordingly suggested.

2. Two approaches are possible. The first consists in comparing the rates of runoff of two or more basins of different percentage forest coverage on the basis of a detailed study of their geomorphological, geological and hydrogeological features (method "A"). The second involves a study of the runoff fluctuations in a given basin over a period of several years during which the forest coverage varies, while excluding the influence of meteorological factors (method "B").

3. In the problem of annual runoff, method "A" involves the selection and comparison of basins in which the difference in physico-geographical conditions acts predominantly in the same direction on the runoff value. Factors governing surface and underground runoff are taken into account simultaneously. Marshiness and flat relief are considered factors diminishing the annual runoff. Geological and hydrogeological conditions are accounted from the point of view of their influence on; a) infiltration capacity of the basin surface, b) return of moisture to the atmosphere by evaporation and intensity of seepage into horizons lying below the sphere of action of the root systems of plants, c) degree of drainage of seepage water by the hydrographic network of the basin in question, d) underground water exchange with adjacent basins, e) loss of part of the water to horizons below the river drainage sphere of underground waters.

4. According to method "B" the influence of the forest coverage on the annual runoff is estimated by assuming the effect of precipitations on the annual runoff factor to be insignificant, beginning from a certain limit, and by selecting such years for calculating the rate, wherein the conditions influencing the runoff fluctuations in the compared groups are approximately the same.

5. In the problem of surface runoff it is interesting at present to apply method "B". Analysis of surface runoff (Ys) as precipitation (X) curves has shown that the runoff factor K increases as the precipitations grow. The branch representing soils of low permeability is characterized by a substantial increase in K when the difference in precipitations is considerable. With more permeable soils, the influence of the precipitations on the value of K is somewhat weaker. In basins with highly permeable soils this influence can be left without special consideration even at a difference of precipitations of about 100 mm, and if the difference is around 50 to 60 mm it can be neglected altogether. The same refers also to basins of given soil composition but with respectively strong and weak pre-flood (for instance autumnal) soil moistening. Therefore the surface runoff is observed to increase with gradually decreasing forest coverage in the following cases:

a) When, with less precipitations, the average value of K for a year group of lower forest coverage is higher than for the previous year group. An observation period of about ten years in each group is sufficient to exclude the influence of autumnal moistening (Po) and the snow melting intensity (i).

b) When in the groups under comparison the runoff factor corresponds to a period of minimum forest coverage, higher than in the first group, the precipitations being above normal in both cases.

c) Ditto, when the earlier years in the groups under comparison have smaller precipitations but their difference is small (about up to 50 mm).

d) When analysing families of curves $Ys = f(X_1 + X_2, Po)$, when the points corresponding to the years of least forest coverage fall to the left, their separation not being due to an elevated value of i.

6. In the problem of underground runoff, determination of underground feed requires that sources not related hydraulically to the river be taken into account. Genetic division of the hydrograph, which does not always give accurate results, can be evaded by the use of water balance equation criteria if Ys values measured directly on small water sheds are available. It turns out that the total summer evaporation in a forest may be higher, and the underground annual runoff greater than in a field, provided the following conditions are observed in districts devoid of summer-autumn floods:

$$I_{Sp}^{forest} - I_{Sp}^{field} > Z_{Su}^{forest} - Z_{Su}^{field} + r^{forest} + Z_{Su}^{forest} + Z_{Su}^{field}$$

where I_{Sp} is the infiltration during the spring period, Z_{Su} is the total evaporation in the course of the summer, r is the precipitation retention by tree crowns.

In a more general case the water balance criterion for the positive role of the forest (in the sense of increasing the underground runoff) may be written as follows:

$$I_{Sp}^{forest} - I_{Sp}^{field} > Z_{Su}^{forest} - Z_{Su}^{field} \quad \text{at} \left(Z_p - Z_{Su}\right)^{forest} = \left(Z - Z_{Su}\right)^{field}$$

$$\text{and} \left(I - I_{Sp}\right)^{forest} = \left(I - I_{Sp}\right)^{field}$$

where I and Z_p are the annual infiltration and evaporation respectively.

The value of I for any time interval can be determined from the expression

$$I = x - \Sigma Z_s - Y_s \pm \Delta S,$$

ΣZ_s = total evaporation from plant, snow and water surface $(\Sigma Z_s = Z_{Su} + r$ where Z_{Su} is the evaporation from the snow and water surfaces);

ΔS = change in moisture supply on the surface of the basin (total per year over a period of several years $\Delta S = O$).

7. First experience in the use of the method developed shows that if the annual runoff to a river with a more wooded watershed is higher or equal to that of less wooded rivers this is not due solely to underground runoff which, as hed been assumed previously, completely compensates the surface runoff, but to small differences in the surface runoff itself. Cases are even observed where the runoff of autumn floods on wooded rivers is higher than on rivers with a low percentage forest coverage. This is evidently dur to the difference in the actual amount of precipitations not registered by the network of rain measuring stations or snow measuring surveys. Aside from orographical causes this is evidently a result of the influence of the forest itself on the precipitation.

RÉSUMÉ

L'auteur expose et compare les deux méthodes possibles pour rechercher la dépendance du débit des cours d'eau du degré de couverture du bassin par la forêt.

La première méthode consiste à comparer les taux d'écoulement de deux ou de plusieurs bassins avec des pourcentages différents de forêts en ne perdant pas de vue les conditions géomorphologiques, géologiques et hydrogéologiques particulières de chaque bassin.

Dans la seconde méthode, on étudie la fluctuation de l'écoulement dans un bassin donné au cours d'une période de plusieurs années pendant lesquelles la couverture varie, en s'efforçant d'éliminer l'influence des facteurs météorologiques variant d'une année à l'autre.

At present, as a result of a large number of experiments, the hydrological role of a forest with respect to its influence on individual conditions governing the intensity of elementary runoff and water infiltration in soils is comparatively well known. But on the whole we are unable as yet to give a well grounded answer to the question of how the forest coverage of a water basin affects the rate of annual river runoff in the long run. The qualitative aspect of the question is not yet sufficiently clear, even after the test fellings that have been made on small water basins in various countries with parallel observation of the runoff.

Unquestionably, the most promising is the use of data on the runoff from real water basins several hundreds and thousands of square kilometres in areas enclosed by hydrometric structures of a network of hydrometeorological stations. A great deal of facts covering many years' observations have now been accumulated, and comparison of these facts with the data on the forest coverage and its variation in time should give very important conclusions.

There have already been attempts made along this line, but they have not given the desired results. The faultiness of the methods used for comparing the percentage forest coverage and the magnitude of river runoff has raised doubts as to the correctness of the conclusions drawn and the recommendations made, so that the controversy with respect to the influence of forests on rivers did not decrease.

The chief shortcoming was that in comparing the runoff in basins of various forest coverage no attention was paid to such factors as relief, soils and grounds, geological structure, etc., and in studying the runoff from basins with systematically decreasing percentage forest coverage no proper allowance was made for climate fluctuations.

It should be emphasized that two approaches are possible. The first consists in comparing the runoff rates of two or more basins with different percentage forest coverage (referred to here as method "A"), and the second involves a study of the runoff fluctuations in a given basin over a short period of years (method "B").

It should not, however, be thought that it is easy to take proper account of all the natural conditions besides forest coverage. In attempting to eliminate the gap indicated above we encounter certain difficulties. They are due to the fact that the dependence of the chief hydrological parameters, and especially of the annual runoff rate, on geo-morphological and soil-geological conditions have been studied very little, and for meteorological conditions no objective criterion has been developed as yet to enable complete exclusion of their influence.

Therefore, in order to make proper use of method "A" the separate influence of all the main physico-geographical factors must be considered and possible methods elucidated for assessing their role in the formation of the runoff in the basins under study. As to method "B", it is necessary to determine how separate years or periods of the many years' series of runoff observations can be reduced to a "common denominator" with respect to climate.

After a brief grounding this report gives the results at which we arrived after working on these questions in special application to problems of forest hydrology.

Surface Runoff

In application to the question of surface runoff method "B" is just now the more interesting one, because with its aid, if data on the economic

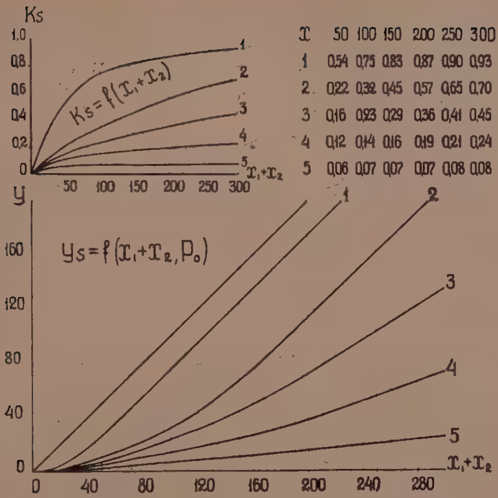

Fig. 1 Dependence of runoff factor on precipitations.

utilization of the territory after the forest has been cut down are available, we can establish which factors were the most important for increasing the runoff: the change in water permeability of the soil or the change in the conditions of snow melting. To exclude the influence of meteorological factors, and primarily of precipitations, it is natural to take advantage of the runoff coefficient, but analysis of the curves of dependence of the surface runoff Y_s on the precipitations (Fig. 1) showed that the runoff factor K_s is a certain function of those precipitations. It can be seen from Fig. 1 that the dependence

$$K_s = f(X_1 + X_2, P_o),$$

where $x_1 + x_2$ are the water reserves in the snow and precipitations during the snow melting period, and P_o is the autumnal soil moistening, is expressed by a family of curves convex towards the x axis, and that K_s rises on the whole with increasing precipitations. The branch referring to the strongest autumnal moistening (or in general to sparingly permeable soil grounds) is characterized by a charp upsurge of K_s at precipitations below standard (curve 1), while the effect of the precipitation on the value of K_s grows weaker in passing over to more permeable grounds. (Curves 3 to 5). With low autumnal moistening of the soil this effect may be left without special consideration even if the difference in precipitations is of the order of 100 mm. But when the difference is about 50—60 mm it may be completely ignored. Therefore, increase in the surface runoff under the influence of gradual forest removal is observed:

(a) when with smaller precipitations the average value of K_s for a group of years with lower forest coverage is higher than for a group of earlier years. An observation period of about ten years in each group is sufficient for elimination of the influence of autumnal moistening (P_o) and the snow melting intensity of both forest and field (i).

(b) when in the groups under comparison the value of K^s corresponding to the period of lowest forest coverage is higher than in a group of earlier years, the precipitations being above standard in both cases.

(c) ditto, when in the groups under comparison the earlier years have less precipitations, but the difference between them is small (approximately up to 50 mm).

(d) when analyzing a family of

$$Y_s = f(X_1 + X_2, P_o)$$

curves in which the points corresponding to the years of least forest coverage fall on the left, if their separation is not due to an elevated value of i.

Subsoil Runoff

In applying method "A" to this problem the separate influence of the following factors must be taken into account. 1. Relief. 2. Infiltration capacity of surface. 3. Aqua-physical properties of soil-grounds with respect to their influence on evaporation and on the intensity of water seepage below the sphere of action of the root systems of plants. 4. Geological structure of the river basin with respect to its influence on the completeness and perfectness of seepage water drainage by the hydrographic network of the basin in question, underground water exchange with adjacent basins along water-bearing horizons lying at not very great depths below the surface and opened by the river network, underground runoff due to artesian waters with sources outside the basin and loss of part of the water below the sphere of river drainage, including losses in river beds.

It may be considered that in the middle latitudes the relief affect the underground runoff only when the soil is highly permeable to water, because the higher infiltration due to more gentle slope only increases the evaporation if the evaporability is large enough.

The infiltration capacity of the surface should be assessed not only by the particle-size distribution of the grounds but also by the type of soil formation on them. If we take advantage of the data obtained by soil scientists, a quite definite conclusion can be drawn with respect to the infiltration capacity, consisting in that the latter should be lower for podzol soils than black earth (with comparable particle size distributions of the soil rock). The reason for this is, on the one hand, the existence in podsol soils of a dense illuvial horizon at a depth of about 30 cm, which is rather impervious to water and, on the other hand, the grainlump structure of black earth, which is especially favourable for infiltration. The infiltration capacity of grey forest earths is also lower than black earths, but there are data to the effect that it is lower in those earths than in podzol soils.

In taking account of the aqua-physical properties with respect to their influence on evaporation (item 3) it must be remembered that on passing gradually from slightly permeable grounds to grounds of high infiltration capacity, a specific phenomenon occurs. Beginning with a certain limit, no matter how high the infiltration increases further, on condition of complete drainage of seepage water, further growth of the evaporation becomes impossible. It may be assumed theoretically that with the above indicated favourable conditions the value Zp (Fig. 2) beginning at a definite point becomes constant for a certain period of time and then with further growth of the permeability and drop of the moisture capacity (in passing over to the coarsest pure sands) becomes even somewhat lower, despite the growth

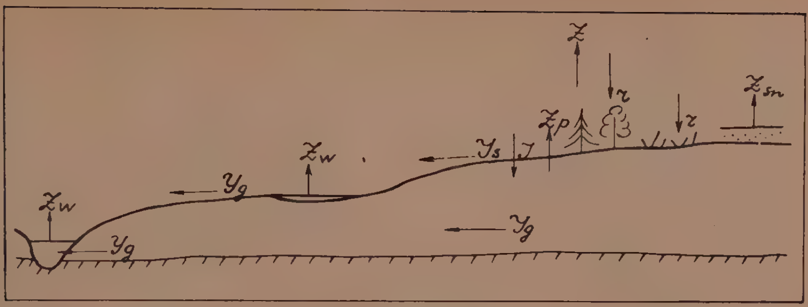

Fig. 2 Component elements of the water balance of a river basin.

of J. Keeping this fact in mind, we can, despite the small quantity of empiric data, conclude that the dependence of the underground runoff in combination with the infiltration and water-retaining properties of soil-ground is expressed by a curve of parabolic shape, like that shown in Fig. 4.

The degree of influence of the factors indicated in item 4 is established in each separate case depending on the actual geological and hydrogeological conditions. As shown by way of example in Fig. 3, in the region of development of glacial deposits, if there is a layer of fluvio-glacial sands between the loamy capping and the moraine (basin I) an elevated value of the underground runoff (case I, e), or, on the contrary, a reduced value (case 1, g) compared to basin II may be erroneously ascribed to the influence of the forest.

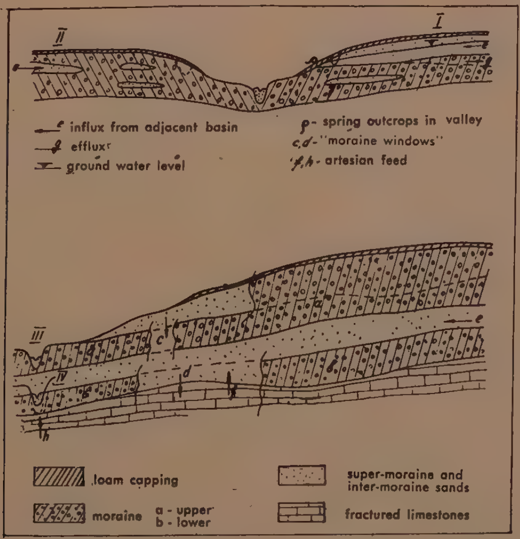

Fig. 3 Influence of geological structure of a basin on underground river runoff.

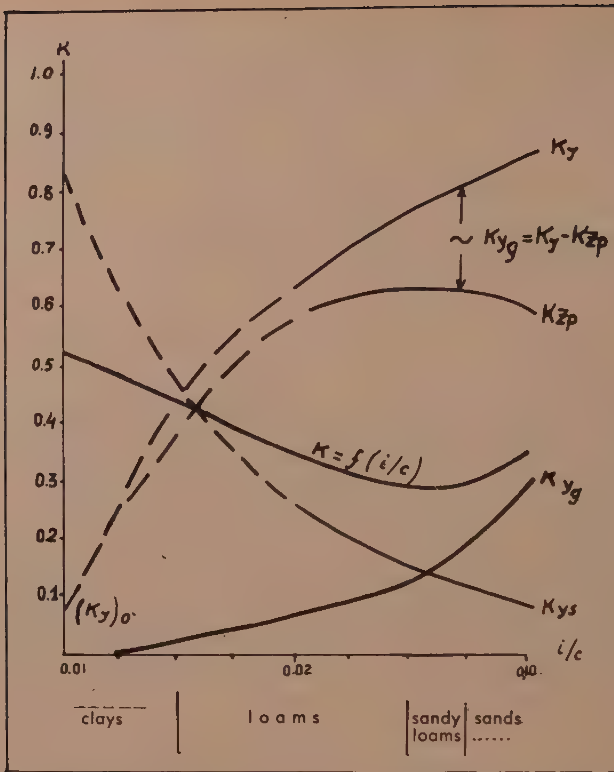

Fig. 4 Dependence of annual runoff factor on physical properties of ground.

If the river bed is situated lower, but the river has not yet cut through the bed of the first water stop (III, Fig. 3) the presence or absence under it of water-permeable deposits will not affect the underground runoff considerably in compared basins with different forest coverage, but if separate "windows" occur in the moraine, through which the water can flow downwards freely (case III c), the basin can no longer be compared with another which lacks the sandy layer.

There will also be no considerable difference in the conditions for underground drainage in the presence or absence of inter-moraine sands between case "a", and case "c", where there are feed windows. This is due to the fact that under condition IV a there is no water-bearing horizon in the sands (the surface and underground watersheds coincide) while under condition IV c the rivers in the basins under comparison drain the same water from the water-bearing horizon in the super-moraine sands.

The fact that in case IV (c, d) the sands reduce the possible underground runoff, while in case IV (a, d) they do not cause any special changes, requires no special explanation.

If the watersheds do not coincide and there is an influx of headless or low-head inter-moraine waters from an adjacent basin (IV e) there will be

an additional increase in the underground runoff in the cases (a, b) and (c, b), which should be taken into account when comparing the basin under question with another which has no water-permeable interlayers. But in the case (c, d) there is a certain indefiniteness which can be eliminated only after special hydrogeological investigations. If follows from the above, by the way, that in comparing the underground runoff of the same river in two lines of direction with different depths of cut and different percentage forest coverage of the corresponding water basins, it cannot be considered, as was the custom previously that the underground runoff always increases with lowering of the erosion basis. This would be true only when:

$$I - \frac{\triangle Q}{Q} > \frac{F'}{F}$$

where $\triangle Q$ is the additional influx of water due to increasing the depth of cut, F' is the area of the basin corresponding to the discharge $Q + \triangle Q$, F is the area of the basin corresponding to the discharge Q.

Artesian water (f or h) will be "foreign" to the basin in question if their source is beyond its boundaries. In this case the forest coverage of the basin has no relation at all to the increased underground runoff registered in the line of direction IV.

For a long time the possibility of greater forest growth increasing the underground runoff of rivers was questioned owing to the numerous factors of higher total evaporation in a forest compared to fields during the vegetation period. But it follows from the water balance equation that the total summer evaporation and even the total annual evaporation may be higher, and the underground runoff greater, in a forest than in a field. Indeed, for average many-year conditions the water balance of a river basin (Fig. 2) can be expressed by the following equations:

$$J - Z_p + Y_g \qquad (1)$$

$$X - \Sigma Z_s = Y_s + J \qquad (2)$$

where J ist the infiltration of water into the soil, Z_p is the total loss of water from the soil by evaporation into the atmosphere (transpiration and physical evaporation), Y_g is the underground runoff, ΣZ_s ist the evaporation from the surface of plants, snow and water; the rest of the denotations are known:

Assuming that $Z_p^{forest} > Z_p^{field}$ owing to the fact that $Z_{p.\,su.}^{forest} > Z_{p.\,su.}^{field}$

$$\text{and } (Z_p - Z_{p.\,su.})^{forest} \leqq (Z_p - Z_{p.\,su.})^{field} \qquad (3)$$

and similarly: $J^{forest} > J^{field}$ while $J_{sp}^{forest} > J_{sp}^{field}$,

$$\text{and } (J - J_{sp})^{forest} \leqq (J - J_{sp})^{field} \qquad (4)$$

where su and sp are the summer and spring respectively
we can write, according to equation (1):

$$Y_g^{forest} = (J - J_{sp})^{forest} - (Z_p - Z_{p.su.})^{forest} + (J_{sp}^{forest} - Z_{p.\,su.}^{forest})$$

$$Y_g^{field} = (J - J_{sp})^{field} - (Z_p - Z_{p\,Su})^{field} + (J_{sp}^{field} - Z_{p\,Su}^{field})$$

hence: $Y_g^{forest} > Y_g^{field}$, if : $J_{sp}^{forest} - J_{Sp}^{field} > Z_{p\,Su}^{forets} - Z_{p\,Su}^{field}$

Condition (3) is not essential, because in the fall and winter period the values of Z_p in the forest and in the field are very small. But according to equation (2) condition (4) with equal values of X is equivalent to the following for the summer-fall and winter periods:

$$(\Sigma Z_s + Y_s)^{forest} = (\Sigma Z_s + Y_s)^{field}$$

or for regions where the summer-fall floods are not great, approximately:

$$\Sigma Z_s^{forest} = (Z_{sn} + Z_w + r)^{forest} = (Z_{sn} + Z_w + r)^{field}$$

where Z_{sn} is the evaporation from the snow, Z_w is the evaporation from the water surface of any of its temporary accumulations on the surface of the soil, at the outcrops of springs and on the waterflows (rivers, rivulets and floods), r is the part of the precipitations trapped by the tree crowns or the field vegetation and lost afterwards by evaporation.

Ignoring the difference in the values of Z_w and assuming that r is not high in the field, the water balance criterion of the positive role of forest (in the sense of increasing the underground runoff) can be written still shorter, without conditions (3) and (4) as follows:

$$J_{Sp}^{forest} - J_{Sp}^{field} > (Z_{Su}^{forest} - Z_{Su}^{field} + r^{forest} + Z_{Sn}^{forest} - Z_{Sn}^{field})$$

considering that $Z_{Sn}^{field} > {}_{Sn}^{forest}$.

The use of method "B" in the problem of the underground runoff is difficult in the pure form because in most cases it is not known over how long a period preceding the season of underground runoff under study the meteorological conditions have to be compared. In this case, if a series of observations are available for a period of 40 to 50 years, the average value of underground runoff in two groups for 10 to 15 earlier years, when the forest coverage was maximum, and for 10 to 15 later years, when it was minimum, can be compared without allowance for meteorological conditions. Another way is to select two adjacent basins on one of which (I) the forest was cut down to a great extent and on the other (II), the forest coverage did not change (it makes no difference whether the coverage was large or small), and to plot the annual values of Y_{gI} against the corresponding values of Y_{gII} on the co-ordinate field, with the purpose of investigation the nature of the relation $Y_{gI} = f(Y_{gII})$. As the common meteorological conditions (excluding the effect of the forest itself) are identical for both basins over the entire period of observations, the points corresponding to the earlier years, if the influence of the forest on the underground runoff is substantial, should fall to one side (to the left of the middle line of the relation if the ordinate axis belongs to basin I), while the points corresponding to the latest period should fall on the other. The possibility of using this simple method ocurred to us recently in working on material concerning the rivers Oka and Desna, and we recommend its use for other objects.

Annual Runoff

Here, to ground the use of method "A" we examined the effect of the so-called "physico-geological" factors on the rate of annual runoff. We came to the conclusion that the rate of annual runoff of rivers is a direct function not only of the climate, but also of the relief, the infiltration and water-retaining properties of the soil grounds and the geological structure of the basin, though the influence of these factors is not very large. The opinion that these factors affect the rate of runoff only indirectly through precipitations and evaporation cannot be considered correct.

The rate of annual runoff decreases in passing from basins with considerable inclines to basins with more gentle relief. The degree of influence

of the incline on the annual runoff on sparingly permeable grounds may be considered approximately equal to the degree of its influence on the runoff of floods. We denote by Y_1, Y_{g_1}, Y_{s_1}, J_1 and Z_{p_1} all the elements already known to us for the basin with the greater inclines and respectively by Y_1, Y_{g_2}, Y_{S_2}, J_2 and Z_{p_2} the same elements for the basin with the more gentle relief. Over a sufficiently large range of clayey and loamy soil-grounds

$$\triangle J \cong \triangle Z_p$$

where $\triangle J = J_2 - J_1$ and $\triangle Z_p = Z_{p_2} - Z_{p_1}$; therefore according equation (1)

$$Y_{g_2} - Y_{g_1} = J_2 - Z_{p_2} - (J_1 - Z_{p_1}) = 0$$

$$\text{and } \triangle Y \doteq Y_1 - Y_2 = \triangle Y_s$$

For ordinary condition, for instance, when the incline in the basins under comparison varies from 0.02 to 0.05, its maximum effect in increasing the rate of runoff may be estimated at 15 per cent.

As was the case in passing from a basin with steep inclines to a basin with a sloping relief gradual weakening of the surface runoff and increase of infiltration are observed also when the permeability of the grounds increases with the same incline. Taking into account the above remarks as to how Z_p varies with growing permeability and decreasing moisture capacity of the grounds (see section on underground runoff), we can get an idea of the nature of the dependence curve of the annual runoff factor K on the physical properties of the grounds on the basin surface. This question has not been elucidated in hydrological literature.

In regions with small amounts of annual precipitations the annual runoff factor in passing from heavy soils to lighter ones will drop perceptibly, after which the curve smoothes out and has a very insignificant rise at its end. If, however, the precipitations are large, the above mentioned effect of lowering of the share of evaporation begins to manifest itself earlier. Therefore, various precipitations will have their own corresponding curves, similar to the curve K = f (i/c) in Fig. 4, each of them giving different values of K for the same ground, depending on the precipitations. These curves are only of theoretical significance, because in nature we have to deal not with grounds, but with various kinds of soils, the water permeability and water retaining capacity of which will vary greatly depending on the degree of differentiation into separate genetic horizons and the packing of the latter by washing in of silt fractions, on the type of macro-and micro-texture, on the water resistance of the aggregates, the nature of the cracks, etc. But in comparing relatively woodless and wooded basins located in the same climatic zone the problem is made easier by the fact that the type of the soil with similar particle size distribution of the solid rock will be the same, and the difference in the nature of the alluvial "humus" horizon between the forest and the field may be attributed completely to the forest effect sought.

Fig. 4 presents the results of an analysis made by us of the possible influence of different particle-size distribution of the solid rock with similar-type soil formation in conditions of a given climatic region (for the example of the podzol soils in the central European part of the USSR). The infiltration and water-retaining capacity of soil-grounds is expressed

by the conventional index "i/c" equal to $\frac{1}{P+10}$ where P is the content of physical clay in per cent. K_{Y_S}, K_{Y_g}, K_J and K_{Z_p} are respectively the factors of surface runoff, underground runoff, infiltration and evaporation obtained by dividing the values Y_S, Y_g, J and Z_p by the annual precipitations.

It has been shown how with growing infiltration capacity of the soil the value of K_{Y_S} drops, while that of K_J increases, obeying the equation

$$K_J = 1 - K_{Y_S} - \frac{\Sigma Z_S}{X}$$

which follows from equation (1), and how the value Z_p which grows at first with J, afterwards begins to fall off.

In principle, the value of K can be obtained by simple algebraic addition of the above enumerated coefficients, because

$$K = \frac{Y}{X} = \frac{Y_s}{X} + \frac{J}{X} - \frac{Z_p}{X} = K_{Y_S} + K_J - K_{Z_p}$$

In plotting the K_Y curve we assumed that the initial infiltation $(K_J)_o$ equals 0.1. It actually reflects the insignificantly small infiltration capacity of heavy clays, but would be quite justified, however, only if the bulk of the annual precipitations moistened the soil not more than several times a year in large portions. Actually, a considerable part of the summer precipitations fall out in small quantities and are completely lost by evaporation without surface runoff. Therefore, accepting as the lower limit of flow-forming precipitations the sum of those precipitations which fall out at a rate not less than 5 mm per 24 hours, we orientated the left part of the K = f(i/c) curve towards the value K 0.5 corresponding to this limit.

Despite the partial conventionality of these assumptions, it can be concluded that the annual runoff factor on basins with medium-loamy and light-loamy sand-loamy soils is lower than on basins with clayey and heavy loamy soils. Sandy soils will differ little in K value from loamy sand and light-loamy soils. The influence of the inner geological structure of the basins has been discussed already in the section devoted to underground runoff.

As to the influence of marshes, according to the latest investigations made in the USSR a small quantity of these does not tell substantially on the annual runoff. But if the water basins are very marshy (25—30 per cent) the rate of annual runoff will evidently drop, this being due not only to the action of the marshes themselves, but also to the aggregate of physico-geographical factors which caused them to form.

On the whole, though it has been found possible to make a quantitative estimation of the influence of certain physico-geographical factors, the conclusion concerning the part played by forests drawn from a comparison of various watersheds by method "A" is so far only qualitative. It is necessary, in selecting basins, to see that the difference in relief, soil-ground, geological structure and marshiness should influence the rate of runoff predominantly in one direction, resorting to approximate quantitative estimation of the influence of not more than one of these factors if it acts in the opposite direction to all the others.

In using method "B" it is desirable, for quite obvious reasons, to take for comparison primarily the extreme years or periods in the available series of observations, to ensure the greatest contrast in forest coverage.

The relation between the annual runoff factor and the precipitation becomes considerably weaker compared to the surface runoff factor, becauce in a zone of insufficient and moderate moistening the larger part of the summer precipitations, irrespective of their yearly variations, is expended by evaporation. This can be taken advantage of to exclude the influence of meteorological conditions when analyzing the reasons for a change in the annual runoff. However, the underground component and the factors affecting its variations must not be forgotten (see section on underground runoff).

In concluding, it may be noted that our experience in studying the influence of forest coverage on the annual runoff of rivers according to the above-described procedure shows that in those cases when the annual runoff on a river with a more highly forested water basin is higher than on a less forested river, or is equal to it, this is due not only and not so much to increased underground runoff, as was believed previously, but mainly to the fact that the difference in surface runoff, which is of the greatest significance in the annual total, is not great. In analyzing what the annual runoff in wooded and sparingly wooded rivers consists of, we even came across such cases where the fall floods were somewhat higher in the first case. Obviously, the influence of the forest itself tells somewhat on the increase in precipitations, on the conservation of small reserves from evaporation and blowing, etc. In treating the data of a network of meteorological stations it is absolutely necessary, therefore to take into account whether they reflect, as to denseness and location, this evidently quite important aspect of the effect of forests on river runoffs.

ON THE QUESTION OF CONTROLLING GROUND WATER RUN OFF BY PINE AND FIR FORESTS

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SUMMARY

The region of investigations is situated on a low watershed between two small rivers, entering into the basins of the rivers Moskva and Kliazma. This region has a moderate-continental climate with a warm rainy summer and frosty winter. The yearly total of precipitations equals 560 mm and the mean yearly air temperature 4.1°C.

On the fairly even surface of the watershed formed mainly by fluvio-glacial sediments are developed pine-fir forests in big massives, that often occupy 10 and more km². Podzolic soils are situated directly upon fluvio-glacial sands with a granular texture; grains are more often of medium and fine size. These sands are 25-30 m thick. They occur on Upper Jurassic (Oxfordian-Callovian) clays, composing a reliable waterresisting bed of the Sub-Jurassic waterbearing horizon.

Waters of this horizon with free surface are at a 0.5-10 m depth and supplied on account of infiltration by atmospheric precipitations. Expenditure of waters belonging to this horizon is: evaporation, transpiration of vegetation and subsoil discharge towards the draining rivers.

Studies of regime and balance of ground water were carried out with the help of a number of observation bores and hydrodynamic analysis of oscillation of level which was accomplished with the help of the method of final differences.

RÉSUMÉ

La région des recherches est située dans un terrain bas situé entre deux petites rivières appartenant aux bassins des rivières Moskva et Kliazma. La région a un climat continental modéré avec un été chaud et pluvieux et un hiver avec gelées. Les précipitations annuelles s'élèvent à 560 mm et la température moyenne annuelle de l'air est de 4,1°C.

Des forêts de pins et de sapins en massifs de 10 Km² et plus couvrent la surface relativement unie des bassins formés de sédiments glacio-fluviaux. Le sol de la forêt repose directement sur les sables glacio-fluviaux avec une texture granulaire comprise entre celle des sables fins et moyens. Ces sables ont une épaisseur de 25 à 30 m. Ils recouvrent des argiles de l'Oxfordien-Callovien (Jurassique supérieur).

Les eaux de ces nappes libres sont à 0,5-10 m de profondeur et sont alimentées par l'infiltration des eaux atmosphériques.

Des études du régime et du bilan des eaux souterraines ont été entreprises en se basant sur les données d'un certain nombre de puits d'observation et sur l'analyse hydrodynamique des oscillations de niveau par la méthode des différences finies.

Many sided hydrological role of forests includes their interaction with run off, regime and on the whole with balance of ground water. In spite of quite a long story of the problem of the effect of the forest on ground water up to the present moment there is no common opinion on qualitative and quantitative aspects of this influence. The main reasons of controversial views on these problems seem to be in imperfect investigation methods applied in studing hydrological role of forest, in complexity of this role and in its different manifestation in various climatological, soil-geological and hydrological conditions.

In our paper we deal with the role of pine and fir forest in forming and controlling ground water run off according to the data obtained by us when studying regime and balance of this water on one of hydrological stations.

The investigation area is situated between two small rivers, included in the basins of the Moskva and the Klyazma rivers.

As to climate it is of moderate continental one with warm rainy summer and frosty winter, annual amount of precipitation being 560 mm and mean annual temperature 4 . 1° C.

On a comparatively flat surface of this area the soils of which are mainly composed of fluivo-glacial sediments big portions of this area are covered with pine and fir forests, many plots being 10 square kilometres and often even more.

Podsol soils lie directly over fine grained and middle grained sands from 25 to 35 m. in thickness. In their turn sands lie on upper Jurassic (Oxfordian-Kalevian) clays which are reliable waterproof bed of Jurassic aguifer.

Water of this horizon with the level contacting atmospherical pressure (free level) is from 0.5 to 10 m. deep and is recharged at the expence of atmospheric precipitation. The water of this horizon is spent on evapotranspiration and underground run off to the draining rivers.

Tests of regime, balance of ground water were performed all over the chosen area more detaily on balance plots of approximately 10 hectares each.

In all, three such plots were chosen; one in western pine and fir forest, with ground water level ranging from 3 to 4 m. below surface level; another in northern forest with ground water level from 0.5 to 1.5 m. deep and, at last, the third one being the glade with ground water level ranging from 2.5 to 3 m. deep. The glade is open from the south.

Movement of moisture in aeration zone, seepage of precipitation, evaporation from surface as well as from ground water level were studied on these plots. Some meteorological factors were also being observed.

Geological features of the glade and western forest are analogous. They found in northern forest at the depth of 6 meters lacustrineglacial clays ranging from 1.5 to 2 meters in thickness which divided the main over Jurassic water bearing horizon into two subhorizons. Of them, the upper one with free surface has the level which is from 1.5 to 2 meters higher than piezometric level of the below subhorizon. Intake occurs at the expense of seepage of atmospherical precipitation all over the area.

The lower subhorizon which has local head stretches to the glade in the form of free horizon (horizon which contacts atmospherical pressure) since there (on the glade) the above mentioned clays are not present.

The upper subhorizon is about 5 m. thick; the lower one is from 20 to 22 m. thick.

The western pine and fir forest where the ground water lies somewhat deeper may be referred to the second bonutas, it also has fir undergrowths and comparatively dry surface with overground vegetation of mesophites.

Root system of the most common pine trees which are 50 to 60 years old is mainly established near the surface within upper (not less than one meter thick) zone of aeration. Northern forest with not very deep level of ground water bears a relation to the third and the forth bonitas with surface vegetation of mesogigrophites and with moist, often damp soils.

The root system of trees comes directly into the zone of capillar saturation and plunges into ground water.

The glade bordering these forested areas is covered with bean-cereal grasses and on its bigger part it has long fallow lands which were not treated for 6 years.

Studies of regime and balance of ground water were carried out with the help of a number of observation bores and hydrodynamic analysis of oscillation of level which was accomplished with the help of the method of final differences.

Analysis of oscillation of levels was supplemeted with making up the balance, drawing up the scheme of migration of moisture in zone of aeration for the glade and western pine and fir forest with the same depth to the ground water.

Observation bores were bored in the range in the direction of ground water flow which on these test plots was on one plane.

Observation points for checking ground moisture were placed near central bores in each range of bores. Soil samples were taken for obtaining moisture content and value weights in aeration zone by means of thermostatic method down to ground water level in every 10 cm. vertically.

Dates of soil sampling were marked by the time of coming or ending typical periods of seasonal oscillation of water levels. Thus, for example, period of infiltration recharge of ground water, was chosen as well as the period of evaporation losses of ground water, etc; all that made possible to draw up water balances for typical parts of the year cycle as well as for annual periods of a number of years — the long term average.

Let us dwell briefly on the scheme of construction of water balance.

Balance of ground water may be expressed by equation:

$$\mu \triangle H = \frac{Q_1 - Q_2}{\omega} \triangle t + W \triangle t, \ldots \qquad (1)$$

where μ — is parameter, characterizing specific saturation or specific drainage of ground with altering water level for a unit of hight which is often taken by investigators for "water return" or deficiency in saturation;

$\triangle H$ — oscillation of ground water level in some section of tle flow, taken between the middles of two adjoining intervals of the tested range, consisting of three bores for a unit of time $\triangle t$;

Q_1, Q_2 — intake and run off of ground water coming in and going out from a certain section of the flow for a unit of time;

ω — square of horizontal projection of the section of the flow; W — value of recharge of ground water from above at the expense of atmospherical condensations for a unit of time (with positive value, infiltration down to ground water, with negative — evapotranspiration losses).

Balance of moisture in the soil-ground prismoid limited by surface from above, from below by water proof and from the sides by limiting vertical planes drawn in the middle of intervals between adjoining bores, may be expressed by an equation:

$$C_2 - C_1 + n \triangle H = \left(W_a + \frac{Q_1 - Q_2}{\omega} \right) \triangle t, \ldots \qquad (2)$$

where C_1, C_2 — initial and final storage of moisture in soil-ground of aeration zone from the surface down to the ground water table.

n — full moisture capacity of the soil-ground within oscillation of water level.

W_a — quantity of moisture exchange of the areation zone with atmosphere (with positive value — inflow of water from soil surface into aera-

tion zone, with negative value run off of moisture from this zone into atmosphere) for a unit of time; the rest designations are the same.

Knowing coefficient of filtration of water bearing soils, efficiency of flow in its different cross-sections, its rakes and oscillation of levels in time from the first equation (1) and formulas of hydraulics of underground water for each period of time $\triangle t$ we computed values of intake for ground water W. Period of time were taken between the dates of sampling soil for moisture content and corresponded to the periods of even oscillation of level.

From equation (2) for each period of time $\triangle t$ we computed the value of moisture exchange of aeration zone with atmosphere W_a, having calculated moisture storage C_1 and C_2 of the aeration zone in the middle section of the flow, the losses of flowing Q_1 and run off Q_2 water and oscillation of its level $\triangle H$.

Knowing the value of W_a and changes in moisture storage in each layer of aeration zone for corresponding periods of time we computed losses of moisture passing through different limits of layers which enabled us to draw up to scheme of migration of moisture along vertical line of aeration zone for a period of observation.

Analysis of such scheme with due regard to changes of temperature in soilground as well as to other meteorological factors made possible to show up regularity of migration of moisture and the way of its movement in aeration zone.

The outcome of one of balance computations were cited in Table 1 for interpreting of which we shall make the following remarks. See p. 409.

Summing up of positive values of moisture exchange of aeration zone with atmosphere W_a per year gives annual value of seepage of precipitation into soil $+ \Sigma W_a \triangle \tau$; summing up of negative values of the same gives annual value of evaporation of moisture from aeration zone — $\Sigma W_a \triangle$. General evaporation from the soil with the absence of surface run off was obtained by adding the difference between fallen precipitation and infiltration into soil ($N - \Sigma W_a \triangle \tau$) on one hand and absolute value of evaporation of moisture from the areation zone $\Sigma W_a \triangle$ on the other. Here $\triangle \tau$ and $\triangle$ — periods of time with positive and negative values of W_a respectively. The alteration of moisture storage in the upper (1 m. thick) band of aeration zone $\triangle C_1$ was obtained according to the data about final and initial moisture content in this band. The alteration of moisture storage in the middle band $\triangle C_2$ (from the bottom of the first band to capillar rim and in the rim itself $\triangle C_3$ was computed in the same way.

Moisture losses through the bottom of the upper $\Sigma q_1 \triangle t$ and the middle $\Sigma q_2 \triangle t$ bands and indraft of moisture in the zone of full saturation $\Sigma(W \triangle t + V\sigma\delta \triangle H)$ with the level oscillation $\Sigma \triangle H$ for time $\Sigma \triangle t$ were computed by means of consecutive substraction of the value $\triangle C_1$ from the value of intake in the aeration zone ($\Sigma W_a \triangle \tau - \Sigma W_a \triangle \vartheta$); then from the received difference of the values $\triangle C_2$ and $\triangle C_3$ respectively, $V\sigma\delta$ being the volumetrical moisture of aeration zone within displacement of capillar rim. Then subtracting the moisture storage with full saturation of ground $\Sigma n \triangle H$ within changes of the level $\Sigma \triangle H$ from $\Sigma(W \triangle t + V\sigma\delta \triangle H)$ we obtained the value of underground run off from the aeration zone or local intake of transit run off of ground water $\Sigma \frac{Q_2 - Q_1}{\omega} \triangle t$ per year. Full moisture capacity of the ground is designated through n. Data as to moisture storage over capillar rim in the beginning of each period of tests within the height

of the respective oscillation of level $\triangle H$ made possible to obtain the annual value of the storage $-\Sigma V o \delta \triangle H$.

Subtracting this value from the foregoing $[\Sigma(W \triangle t + V o \delta \triangle H)]$, we obtained the annual intake value of ground water $\Sigma W \triangle t$. The latter shows the amount of indraft of moisture from above down to the level of capillar rim at its highest position during the period of tests $\Sigma \triangle t$.

At last, decrease or increase of the moisture storage over capillar rim was computed by us with the help of the following equation.

$$d = -(\Sigma W_a \triangle \tau - \Sigma W_a \vartheta - \Sigma W \triangle t) = -(\Sigma V o \delta \triangle H + \Sigma \triangle C) \ldots \quad (3)$$

The comparative analysis of computed components of balance and movement of moisture in aeration zone for the forest and the glade (table 1) and also outcomes of the above mentioned computations of balance of ground water on all the three plots made possible to come to the following conclusions:

1. For average year, according to the data for the period 1950 to 1953, which was by 35 per cent above normal precipitation (normal precipitation, 560 mm) the module of the local intake of underground run off in northern forest was $\frac{126.0}{31.5} = 4.0$ litre/second for 1 square kilometer, on the glade $\frac{10.3}{31.5} = 0.33$ litre/second for 1 square kilometer.

TABLE 1

Balance and movement of moisture in aeration zone according to average data for the period
1950—1953 years

No.	Balance and movement of moisture	During hydrological year in mm of water layer		
		western forest	glade	difference
1	2	3	4	5
1.	Atmospheric precipitation N	754.6	754.6	—
2.	Precipitation seepage into the soil $+\Sigma W_a \triangle \tau$	544.7	416.1	+ 128.6
3.	Evaporation of moisture from aeration zone $-\Sigma W_a \triangle \vartheta$	309.4	278.7	+ 30.7
4.	General evaporation from the surface $\Sigma u \triangle t$	519.3	617.2	— 97.9
5.	Oscillation of moisture storage in the upper band $\triangle C_1$	+ 4.0	+ 11.5	— 7.5
6.	Moisture losses downwards (+) or upwards (—) through the bottom of the upper band $\Sigma q_1 \triangle t$	+ 231.3	+ 125.9	+ 105.4
7.	Oscillation of moisture storage of the middle band $\triangle C_2$	— 14.4	— 23.2	+ 8.8

No.	Balance and movement of moisture	During hydrological year in mm of water layer		
		western forest	glade	difference
1	2	3	4	5
8.	Moisture losses downwards (+) or upwards (—) through the bottom of the middle band $\Sigma q_2 \triangle t$	+ 245.7	+ 149,1	+ 96.6
9.	Oscillation of moisture storage of capillar rim $\triangle C_3$	+ 3.4	+ 7.6	— 4.2
10.	Inflow of moisture into the zone of full saturation (+) or out of it into upper bands (—) $\Sigma (W \triangle t + V o \delta \triangle H)$	+ 242.3	+ 141.5	+ 100.8
11.	Moisture storage with full saturation within $\Sigma \triangle H$; $\Sigma n \triangle H$	+ 116.3	+ 131.2	— 14.9
12.	Underground run off from aeration zone $\Sigma \frac{Q_2 - Q_1}{\omega} \triangle t$	+ 126.0	+ 10.3	+ 115.7
13.	Moisture storage over capillar rim within limits $\Sigma \triangle H$; $\Sigma V o \delta \triangle H$	+ 45.0	+ 46.8	— 1.8
14.	Recharge of ground water from above $\Sigma W \triangle t$	+ 197.3	+ 94.7	+ 102.6
15.	Alteration of ground water level $\Sigma \triangle H$ (m)	+ 0.29	+ 0.34	— 0.05
16.	Oscillation of ground water storage $\Sigma \mu \triangle H$	+ 71.3	+ 84.4	— 13.1
17.	General oscillation of moisture storage in aeration zone $\Sigma \triangle C$	— 7.0	— 4.1	— 2.9
18.	Outflow (+) or Inflow (—) of moisture storage over capillar rim d	— 38.0	— 42.7	+ 4.7

2. Infiltration of precipitation through the soil in the forest reached 72.2 per cent, and on the glade 55.2 per cent of their total annual amount.

3. General evaporation from the surface in western forest (with water 3 to 4 meters deep) was 97.9 mm less than on the glade, it being caused by reducing evaporation losses by 128.6 mm of the water layer in the forest, due to the fact that precipitation had no time to infiltrate into the soil on one hand and the presence of excess of moisture (by 30.7 mm) losses from aeration zone for evaporation in the forest over analogous losses on the glade.

4. Somewhat bigger losses (about 309.4 mm) of moisture from aeration zone for evaporation as compared to similar losses (about 278.7 mm.) on the glade was predetermined by high rate of transpiration.

5. Thanks to higher rate of infiltration of atmospheric precipitation into the zone of aeration as compared to those on the glade by 128.6 mm for water layer, bigger indraft (by 100.8 mm) of gravity moisture from aeration

zone into the zone of full saturation; also the intake of ground water was (by 102.6 mm) more than on the glade. This fact led to considerably bigger (by 115.7 mm) local intake of underground run off in the forest than on the glade.

6. If during certain years (for the period 1949 to 1955) the glade manifested itself as an area which formed underground run off (with local intake of underground run off up to 63 mm for water layer per year) or as an area which spent this run off by evaporation (to 153 mm per year) the pine and fir forest at the same time with water 3 to 4 m deep always contributed to replenishing this run off.

Considerable recharge of underground run off was observed during dry year of 1954-55.

During certain years on the glade seepage of precipitation down to ground water (positive recharge) reached 46.6 per cent per year and in western forest 37.6 per cent. However, evaporation of ground water (negative recharge) was considerably higher on the glade than in the forest as a result of which the amount of intake of ground water was less on the glade than in the forest which in its turn often led to negative water balance.

7. In nothern forest with ground water ≤ 1 m deep they usually mark evaporation losses of this water. Here evapotranspiration losses amounted to 952.8 mm for water layer in the year of 1954-55 with atmospherical precipitation 515 mm. Somewhat less moisture losses were on border of the forest—461.5 mm for the same year.

With reducing of annual amount of precipitation by 350 mm evaporation of ground water in this forest and on the border of the forest increases by 210 and 260 mm respectively. At the same time on the glade with decreasing precipitation during the same years the losses due to evaporation from ground water is accordingly lower.

During the years with above normal precipitation loss of ground water due to transpiration in northern forest was lowered to 750 mm per year.

Recharge of ground water losses due to general evaporation occurs at the expense of more elevated marshy areas as a result of seepage from forest ponds.

8. Still greater role of aeration zone as a regulator of balance of ground water is marked in western pine and fir forest.

If according to average data for three year period (Table 1) intake of ground water in the forest was 26.2 per cent from the amount of precipitation and on the glade it was 12.5 per cent then during the years with average precipitation similar to those during many year period (as for example in 1950-51 with precipitation 547.2 mm) it (intake) amounted to 48.8 per cent, and on the glade 5.3 per cent from the amount of precipitation, intake in the forest being effected not only at the expense of seepage of precipitation but also at the expense of moisture storage in aeration zone which were accumulated during above average periods of precipitation.

9. It is typical for pine and fir forest where ground water levels range from 3 to 4 m to have somewhat later period of intensification of seepage of melting snow water which is due to the fact that in the forest the surface is more overshaded and the soil is less warmed up. The gap between the beginning of spring seepage in the forest and that on the glade is two weeks. At the same time May precipitation infiltrate in greater amounts in the forest than on the glade. The same may be observed late in the summer and in autumn (August-October) when in western forest seepage of atmospherical precipitation occurs through entire aeration zone. During winter

periods in the same forest the establishing of ascending migration of moisture from ground water flow to the surface is somewhat delayed due to microclimatological features of landscapes studied. (In particular due to the fact that soils in the forest become cool later than elsewhere).

10. In western forest during warmer part of the year, the upper (1 m in thickness) band of areation zone retained about 25 per cent of monthly amount of moisture passing through the soil whereas on the glade within the same band only 20 to 25 mm of water layer are monthly retained from downward of moisture flows.

Accumulated moisture is later spent on general evaporation during drier periods. During the same period of the year within the middle band evapotranspiration losses are 20 per cent of the moisture flowing into it from the upper band during above normal periods of precipitation of the year.

As to the glade the middle band does not retain the moisture coming into it from above.

11. With small values (to 60 mm per month) of moisture seepage into the soil the intake of ground water in the forest is higher than on the glade; reverse phenomenon occurs when seepage into aeration zone is larger than 60 mm of water layer, for a period.

The above given account convincingly points out to the fact that pine and fir forests on fluiviglacial sands in the conditions of moderate continental climate may perform the parts of an accumulator of atmospheric moisture and a regulator of underground intake of ground water run off during one season as well as during many year periods and, at last, of powerful "biological drainage" of excessively damp lands.

In the first case (all other things being equal) indispensable condition is to have aeration zone sufficiently thick, ground water level being ≥ 3.5 m below surface level, in the second case ground water level ranging from ≤ 1 to 1.5 m.

When forests act as accumulators and regulators of underground water intake the run off water is relatively stable and controlled by natural way.

In case of excessively damp lands forests effecting drainage, influence general water balance thus preventing adjacent territories from progressive bogging up.

Great significance of forests as regulators of underground run off and general water balance indicates the necessity of broadening complex investigations connected with the problems of water balance in forested lands under different climatological and hydrogeological conditions with the view of developing efficient measures for controlling water regime of territories.

NATURE PROTECTION AND WATER ECONOMY

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Summary

Water deficiency has recently become a more drastic problem and in many European countries occupies a central position in economic planning. In the meantime, the need for water is still growing which, on one hand, entails further deficiencies and, on the other hand, threatens hydric and biocoenotic equilibrium and leads, at the same time, to encroachment by the steppe. A paramount factor in the maintenance of hydric and biocoenotic equilibrium are forests, which regulate water circulation. Scientific hydrology is concerned with the investigation of these changes and a supervision of the hydro-dynamic of an area. This procedure is called the dynamic water balance and it indicates tendencies of development in water conditions. Hydrologic research should therefore in the end determine the future water balance, i. e. to establish, on the basis of a general economic plan, the balance of the future. The suitable definition of evaporation and transpiration as well as the role of forests and agricultural relations constitute bases of water balance planning.

Résumé

Le manque d'eau est, récemment, devenu plus aigu. Il constitue, dans beaucoup de pays européens, un problème d'importance pour l'économie planifiée. Cependant, le besoin en eau augmente sans cesse. Cela accroît les déficits d'une part, et, de l'autre, menace de rompre l'équilibre hydrique et biocoenotique, tout en conduisant, parallèlement, à l'envahissement par les steppes. Les forêts qui règlent la circulation de l'eau constituent un facteur d'une importance considérable quant au maintien de l'équilibre hydrique et biocoenotique. Dès lors, l'hydrologie scientifique se doit d'étudier ces changements et de surveiller la dynamique du développement des conditions hydrologiques du territoire. Ce procédé indiquant les tendances du développement des conditions de l'eau, nous le qualifions de — bilan de l'eau dynamique. Les recherches hydrologiques devraient par conséquent conduire à l'établissement d'un bilan d'eau futur, c'est-à-dire à l'établissement sur la base du plan général de l'économie d'un bilan en perspective. La définition appropriée de l'évaporation et de la transpiration, ainsi que le rôle des forêts et des relations agricoles constituent la base des bilans de l'eau planifiés.

1. General Remarks

The problem of water supply has recently become a drastic problem not only in countries naturally deficient in water but also those, where, it would seem, there is a water surplus. This problem today occupies the minds of technicians and statesmen of many countries, and articles published in professional reviews and the daily press under such alarming titles as "Wasser die Sorge Europas" or "Water or Death" are to be encountered more and more frequently.

The changes occuring in the hydrosphere in connection with poor regulation of water circulation do not remain without import in the world of plants and animals; to the contrary, they begin a chain of mighty transformations in the latters' biocoenosis. These modifications are often so considerable, that not only do they adversely influence the whole complex of circumstances characterizing a given landscape but also constitute sources of new disadvantageous transformations discordant with the type of land-

scape. Only a solid knowledge of the laws ruling nature and the relations governing the biosphere may avert the pernicious consequences of these changes in the hydrosphere, which infringe on the centuries-old relative biocoenotic equilibrium. In history we can find many examples of disturbances in this equilibrium, ones which brought in their wake biological extermination and the fall of whole national cultures; the valley of Mesopotamia, the desert Kara-Kum, and the barren desert areas of the Near East will for a long time attest to he results of the above process.

The so called phenomena of "encroachment by the steppe" belongs to the category of events which occur in biocoenosis in connection with badly regulated water circulation leading to the upsetting of the biocoenotic equilibrium. This problem, it seems, has found sufficient comprehension and scholarly elucidation, and naturally so, not only in our country but in the whole of Central Europe; consequently it is needless to analyze it closer. However it is to be pointed out that such disadvantageous changes have had their origin in periodical, but recurrent water deficiencies, often caused by man's activity.

Water deficiencies appearing in connection with bad water circulation should become the object of particular interest to naturalists, and more particularly, to scholars concerned with the problem of rational utilization of natural resources, while the part played by periodical water deficiencies in the changes occurring in biocoenosis should be the object of keen research and natural studies.

Biocoenosis and biotop, with their hydrics relations as well as macro- and micro-climate, interact with each other and are in their mutual influence so bounded that the individual phenomena—as a function of several non-constants—are very hard to classify; the dynamics of their changes are difficult to know so as to predict their further progress. Usually, however, at the base of the changes occurring in biocoenosis there stand out the hydric relations forming biotops, biocoenosis and micro-climate character. One can easily see, therefore, that the problem of water deficiencies and of water conservation has an intimate connection with the problem of nature protection and natural resources.

2. Projects of climatic changes and of water balance

It is characteristic of all large scale projects of climate change that they are based on changes of water circulation or the irrigation of large areas. For example, the great project of Atlantrope envisages the metamorphosis of Central Africa's climate; this is to be accomplished through storing up Congo river waters, creating a great Lake Chad and the Congo Sea, irrigating the Sahara and lowering the Mediterranean's water level.

All gigantic projects for changing Europe's climate involve the diversion of the Gulf Stream closer to the Continents' coast, with the purpose of intensifying the continental heating process,—consequently, the prudent direction of water management constitutes the basis of such planning. The huge project of transforming nature and of changing climate in the Caspian-Aral area, worked out by the Soviet engineer Dawydow consists also of changing water circulation and of diverting the abundant waters of North Siberia's rivers at the rate of 10 km^3 of water annually to the drainage areas of the Caspian and Aral Sea basins. This large scale plan, creating a thousand square kilometers of forest zones and enabling the irrigation of large desert

areas, is possible only if an adequate water supply is provided to these areas, once fertile and rich, but today entirely gone to ruin because their hydric equilibrium has been shaken.

Thus the basis of all projects for climate change and nature transformation is the restoration of the equilibrium of water balance as the fundamental condition for biocoenotic equilibrium.

The goal of water balance science, which forms a part of hydrology, is precisely the knowledge of hydric relations and of the character of changes occuring in the local hydrosphere.

The mutual relation between the individual factors of water balance, such as precipitation, evaporation, transpiration, consumption, drainage and water loss has shown in the course of long periods of time some deviation from average conditions; in other words, over a period of years, it oscillates but remains in the neighbourhood of average value. The important point is whether such changes do not acquire some constant tendency in a definite direction which would indicate the constant changes occurring in water relations, which, though very slow, are none the less systematic. Should this be so, then we should have to take into account this tendency as well as the reasons which cause it, in order to cooperate with them or to act against them, as required by the plan of natural conservation.

It is to be noted of course that these problems are here examined against the background of the present age; climatic changes, which occurred many centuries in the past, have not been taken into consideration.

Slow changes occurring under hydrological and climatological conditions entail changes in phytosphere, which in turn cause changes in the animal world. The changes observed in the vegetable kingdom give evidence not only of changes occurring in hydrics and climate but indicate, in addition, that they are at the base of further changes in water circulation and local climate relations. In this way, a chain of causal transformations depending upon each other is set in motion of its own. Here, as an example, we may cite forests' influence on hydric connections and local climate and the interaction of the latter on sylvan environment.

We would certainly be glad to see a natural arrangement of these relations, one which would be lasting and stabilized, which could be impossible to disturb by artificial means. For it could injure the natural biocoenotic equilibrium, and the latter must above all be preserved if the landscape is to be a healthy one. The example of man's improper influence on nature's equilibrium is the excessive exploitation of forests in many ancient countries of the Mediterranean Basin; this process weakened the whole water balance, and indirectly, the whole phisiocoenosis; it brought on, eventually, the economic ruin of these countries.

Provided man enters natural biotop—conscious of the goal and aware of consequences engendered by his activity, and provided that his activity is based on the knowledge of the rules governing nature,—he then may transform the biocoenosis of a given region in a way provoking no pernicious consequences of upsetting the natural equilibrium. By doing so, man may become a useful and cooperative agent in the landscape biocoenosis transformation.

The biocoenotic system, governed as it is by natural equilibrium, is not an inflexible system, for it is submitted to continual, though very slow, changes. Some species perish, others replace them, develop and attain the peak of their development; others degenerate, whereupon they vanish in spite even of often favourable climatologic conditions. In the same way in

the hydric biotopic system there appear continuous oscillations; we may speak, therefore, only of an apparent equilibrium, whose tendency of changes we have to inquire into very assiduously, if we intend to get acquainted with the dynamics of the progress of a given system.

In the problems examined by us we are interested above all in knowing whether this equilibrium remains constant or fluctuates, in other words, whether the system, after having been put out of equilibrium and left to itself, will return to its original condition, or whether these changes themselves will become in fact the normal state of affairs. While managing water and herewith taking into account natural conditions, we ought to investigate, faithfully, whether an oft-noted water loss constitutes a deepening and irreversible symptom, or, after eliminating the cause of that loss, a return to the original equilibrium will ensue.

3. The role of forests in the water balance

During their development, forests change micro-climatic relations and above all greatly modify hydrologic relations and reduce the ground water level, which has already begun to be inadequate for the abundant needs of rich flora. The quantity of water consumption by forests is so considerable that the general balance suffers as a result of it. After a forest's full development is reached, when precipitational waters grow scarce, it draws from ground-waters such large quantities that its waste cannot be covered by the water balance: a deficit appears which is noticeable first in dry years and later even in average ones. Then ensues the process of the forest's retreat from its dominant position; should a man with a devastating economic plan step into this state of equilibrium, destruction of the region's whole biocoenosis may ensue. We observed such a process in the USA at the end of the last and beginning of this current century. It was succeeded by a biological destruction of large country areas and its widely known consequences.

As a further development of the process under discussion two alternatives arise: either, subsequent to forest devastation and the diminution of water consumption, the level of ground water shall again rise and furnish nature the opportunity of a gradual and systematic return to the former forest conditions,—or, the process of steady water diminution, due to existing physiographic and hydrologic conditions, shall become irreversible, in which case the deepening "encroachment by the steppe" will follow.

The symptoms of undesirable water shortage, leading to constant and growing water deficiency, will occur precisely where hydric equilibrium fluctuates and the water shortage becomes an irreversible process. This kind of area requires particular research and study in order to avoid the definitive destruction of the existing equilibrium. The areas most sensitive to unsteady water equilibrium are areas without drainage.

Should nature itself fail to establish a productive equilibrium between the circulating water surplus and its consumption, or should the equilibrium not be regulated in a rational way by man, then the hydric equilibrium will be infringed upon and, consequently, a constantly deepening deficiency will occur. An example of such a process may be observed on the Turkmenian steppes and the Kara-Kum's sands. The restitution of the area's former splendour may by conceived solely in the transferrence of the necessary water masses from another basin in considerable quantity (let us say approx.

10 000 m^3/s). This measure would aim at compensating for the water balance deficiency and would constitute the basis for a great enterprise, known as the transformation, or metamorphosis of nature.

In our climate conditions we have for the most part an apparently constant equilibrium of the physiocoenotic system. Should we leave today's landscape, as it was formed by man's hand, to itself, in time it would start to transform itself into a natural landscape and come back to the primitive state. Forest wilderness of primitive character would appear and take over areas where today we enjoy meadows and cultivated fields.

However, this fact holds true only in the case of forest climate in Central Europe; in general, for individual cases in such areas different conditions can arise, varying with geological conditions, the peculiarity of the site, and so on, in which case this kind of change in the given area may be of durable and irreversible nature.

To investigate the tendency of the hydric conditions is the hydrologist's and naturalist's goal, hard but necessary, if the water direction is to be rational and in accordance with nature's preservation. Otherwise, through ignorance of such processes the development of hydric relations may be directed along the wrong paths. Then man's influence on the apparently reigning equilibrium will become fatal in its consequences.

4. General water balance

In speaking about the water relations of our biotops, we have to determine whether the quantity of water which nature disposes in average conditions is sufficiently large, or too small; in other words, how does the water balance appear? This is the basis of knowledge about the development of relations in biotopy. Let's take, for instance, the example of relations in Poland.

The total quantity of water which falls on Poland's area, on an annual average of precipitation, amounts to 191 billion m^3, that is 191 km^3 of water, which corresponds to the annual layer of 597 m/m precipitation in all of Poland increased by 5 billion m^3 of water from abroad. This average quantity of precipitation is rather unequally divided over the whole of Poland's territory, for there is very sizeable precipitation amounting in spots to 2000 m/m in the Tatras; on the other hand, sites exist in Central Poland where, for instance, precipitation does not attain even 450 m/m. The majority of Poland's area receives precipitation which in normal years does not reach 600 m/m. Central Poland is affected by precipitation depression and precipitation does not exceed even 500 m/m. These are the same areas where encroachment by the steppe has been observed.

Of the total amount of water which falls on Poland's area in the form of 597 m/m of precipitation and 167 m/m of inflowing water, 58,6 km^3 of water flows off to the sea in the course of the average year, which calculated in terms of waters strata on the whole territory of Poland, gives 188 m/m; the remainder, i.e. 136 km^3 of water, in other words the stratum at 425 m/m, constitutes a so called ground evaporation, i.e. evaporation takes account of transpiration, of which the greater part is accounted for by vegetation evaporation and only a part by ground—and cover-evaporation, not to mention an insignificant quantity of consumption i.e. a quantity which does not reenter into circulation since it is consumed by vegetation so as to produce phitomass.

It should be underscored that the aforesaid 425 m/m of ground evaporation as well as 188 m/m of off-flow are average figures for the whole territory in an average year. In many areas of Central Poland there are off-flows of less then 70 m/m, and there are even cases where off-flow drops to 30 m/m. In such areas almost the whole of the water supply is absorbed by vegetation, or evaporates without leaving any surplus. The whole parallel zone of Central Poland is made up of areas where off-flows in normal conditions do not attain 100 m/m.

Ground evaporation, indispensable to the support of vegetation, under our conditions comes to 400-450 m/m yearly and this in areas of Central Poland where the normal annual precipitation does not exceed 450 m/m during the average year. During years of drought the average precipitation in all of Poland amounts approximately to 410 m/m, and in Central Poland falls even below 300 m/m. These figures demonstrate the scarcity of water in Poland, but they also prove the fact that the water balance is attained only with difficulty and solely thanks to the adaptation faculty of flora which, in periods of precipitation poverty, satisfies itself with considerably less water by abating the position of ground evaporation. Yet along with repeated periods of water deficiency there must appear symptoms of change in biocoenosis which testify to encroachment by the steppe.

In the Western areas of Central Europe the water balance appears much better, nevertheless there the problem of water deficiency becomes of very serious concern to the economy, although this state should not be disturbing, in comparison to conditions existing on Poland's area; for example, the area where normal annual precipitation is below 600 m/m, which in our country embraces the greater part of our territory, involves in Czechoslovakia but a small portion of the country. But, after all, Czechoslovakia also does not enjoy over much precipitation and often suffers periodic dryness.

In the surface area of the German Federal Republic, the average yearly precipitation for the 40 years 1891-1930 amounts to 771 m/m i.e. almost 30 % more than in our country.

From the water balance conditions of the G.F.R., when compared to those of Poland, we see in Germany an abundance of surface and ground waters. We must underline the fact that surface waters are the safety-valve of the water balance: in periods of dryness, they are used for local purposes, in those of water surplus, they flow off, sterile, to the sea. In the course of an average year, scarcely a half of the supply which Western Europe possesses is available in Poland.

Likewise the G.D.R. areas, where climatic conditions are similar to ours, have a more favourable water balance. There precipitation is higher than in Poland (643 m/m) as well as the water consumption for vegetation needs; this is testified to by a ground evaporation more intense than in our country (473 m/m in G.D.R. against 425 m/m in Poland).

5. Water reserves in relation to needs

The above data indicate sufficiently how poorly we are provided with water reserves. They likewise prove that at any time we may be facing a deficiency from which it would be impossible to recover simply by decreasing drainage reserves, which would involve the disturbance first of the hydric and, then, the biocoenotic equilibrium. In the greater part of Poland such incidents will of course be sporadic; they will occur merely in dry

periods, for in the global water balance of several years there is plenty of water; but they will often appear in deficient areas, evolving gradually into a constant process and leading to the well known symptoms of encroachment by the steppe.

The fact that stepping in our country has not yet become a clear and explicit phenomenon is to be ascribed, on one hand, to the ability of the flora to adapt to existing conditions and, on the other, to the phenomenon of activising the evaporation. The process of activisation consists in the fact that, for want of sufficient water reserves, ground and cover evaporation decreases, to the advantage of physiologic evaporation, i.e. of transpiration which continues to occur to the same extent as formerly. For this reason, by comparing the results, we see that evaporation in all three cases is identical and reacts little on the quantitative displacement of the individual elements within the general configuration of the water balance. However, the activisation of sterile evaporation has its limits, which are relatively narrow ones.

From the above short review of hydric relations it follows that in all of Poland the water balance is strained and that we are barely "balancing" ourselves precariously on the borders of our needs and potentials. Each additional demand must of necessity lead to a deficiency which will involve unfavourable consequences for one or another of the factors in the balance, leading to disturbances in the established hydrologic equilibrium of the area and, consequently, in the biocoenotic equilibrium as well. Meanwhile, our needs grow larger and larger. Man consumes constantly more water for his sanitary, communal and cultural needs, industrial needs are growing rapidly while agriculture too involves greater demands in connection with its intense forms of cultivation (artificial irrigation); over and above all this, forestry becomes more significant in the water balance, in connection with the improvement of forest resources.

However, it is to be noted that the global amount of water used by industry and man for divers purposes remains insignificant in comparison to the immense amounts of water transpumped and transpirated by flora, which constitute the dominant factor of the whole water balance problem.

Given such a combination of factors as we observe in the Polish balance, practically speaking, only a very small quantity of water, that left at our disposal by the flora, is available to us. The forest itself always absorbs the quantity of water which it needs and regulates the water balance in accordance with natural rules, disregarding our will.

It is vegetation which above all consumes water; therefore each increase in demand of quantities not covered in the established hydric equilibrium must be detrimental to vegetation needs. We should add here that in the interest not only of natural conservation but also that of economy there is need to increase water consumption by flora, in particular in connexion with the goals assigned agriculture for a considerable increase in production and the improvement of our country's sylviculture. That is why any symptom of water deficiency, about which we are more and more informed from various parts of our country, are simultaneously questions of nature protection and economy.

Moreover, the question of pollution of open- and underground waters is tied to the problem of increasing demand for communal and industrial water. In Central Europe, this phenomenon is becoming alarming, quite frankly speaking. As a result of great spoilation, considerable amounts of water are eliminated from the water balance as being out of use and all

the biological life of this water is destroyed. Industry uses larger and larger quantities to cool condensers and engines. While it is true that this water returns to circulation, it nevertheless comes back quite heated, which reduces its oxygen content and causes the cool water loving flora and fauna to perish.

6. Water deficiency

In order better to understand the water deficiency in our areas, the fact should be underscored that these are not water deficiencies on an absolute, but a relative scale. There are water deficiencies which appear when the rising need for water exceeds the means for its satisfaction from the existing reserve, comprised of the off-flow of surface waters. Such an artificial increase of need provided by man's and the economy's growing exigencies remains often inconsistent with the hydric equilibrium of the given area, long since a constant.

The relativity of the water deficiency is at the very root of the fact that water deficiencies appear not only in areas of feeble precipitation and drainage, where the water balance is not easily kept in equilibrium, but also in sections where it seems there is plenty of water, in any event more than in others. In those areas we have water deficiency not because in a natural system there is a deficit of water, but because industry's requirements are too high and a great degree of existing polluted reserves makes their exploitation impossible.

We should not rest satisfied with the fact that water deficiencies exist in our country but are relative and not real, that in natural conditions they do not exist, but they are artificially created by man; for, with the increasing demand, man already contemplates exploiting the mass of water which until now had remained at the disposal of vegetation. As our rivers show water decrease, the ground water level drops, grasses and small reservoirs dry up, and existing water reserves are more and more diverted to purposes the very opposite of their natural ones to which the flora was long ago adapted.

Forestry's condition is better than that of agriculture since it is more difficult to deprive the forests of water, inasmuch as they manage their water problems independently of man, taking it directly "first hand" even before it flows off. All the remaining vegetation is very sensitive to all artificial changes in water circulation.

Apart from the above mentioned relative deficiencies, we may discern other forms of water deficit, perhaps more dangerous from the point of view of nature protection and management of its resources than, for instance, periodical deficiencies. Water preservation fights against periodical deficiencies by equilibrating drainage with the help of retaining reservoirs. However, the most perilous phenomenon is the constant, irreversible deficiencies whose invariably deepening water shortage leads to the destruction of the balance of the biocoenosis in a given area and to its transformation into a desert. This state of affairs may be amended only through climate regulation, by changing water circulation, as for instance, throwing over of large water masses from an other basin with water capacity in surplus.

The struggle against water shortage as well as its overabundance belongs to the goals of planned water economy but the main point is to regulate this planned action not only in accordance with man's needs but also to

take into account the complex needs of the natural biocoenotic system together with hydrologic relations, in order to preserve the natural equilibrium and guarantee a healthy landscape.

7. Projects of water economy

Work done on the basis of planned water economy touches upon varied spheres of economic life and nature itself, as it becomes of urgent necessity to fix the limits of water economy.

While forming water balance in an artificial manner, while influencing water circulation by different means it is impossible to do so freely, for borders exist which can not be crossed. In order to respect the limits of water economy traced by nature herself it is in the first place necessary to become acquainted with all the changes occurring in the actual static as well as dynamic system, which involves foreseeing the progress of changes and relations likely to take place in the future. Here a great sphere of action lies open for naturalists-hydrologists.

In dealing with hydrologic and biologic processes which constitute the links of the water economy chain, we must treat them extremely carefully, and only after acquiring an exact knowledge of the development of those processes. Nature constitutes after all an indivisible entity of all her elements. By changing one of them—for instance the microclimate of the hydric conditions—we provoke a chain of changes in all other elements. The changes occurring in the water balance particularly call for farreaching changes in the total configuration of different organisms and cause repeatedly greater economic losses than gain in new hydrologic conditions.

Nature prescribes for the water economy rules governing biocoenotic groups (ensembles), among these climate. On the other hand, economic rules governing relations between humans enter into account. The disturbance of biocoenotic and hydric equilibrium no doubt constitutes an error which must avenge itself on man, which involves a chain of further consequences often unforeseen by him. However, since life is no longer circumscribed by the limits fixed for it by natural law alone, we must seek a healthy compromise. by arranging relations in nature in such a way that even while infringing upon the natural equilibrium; indispensable harmony may be saved, so as to appease the living exigencies of nature.

8. The dynamic balance

In foresting the changes which will occur in the whole biocoenotic system, in connection with changes in water circulation in a given area, we have a basic problem, one which is indeed not an easy one. Here we arrive at a new conception of water balance, or rather dynamic balance. This new concept, no doubt, will play an important role in the future.

The task of the dynamic water balance is the anticipation of changes which shall occur in the future in the configuration of the hydrologic relations in a given area under the influence of factors which exercise their influence on water relations. This foresight will form the basis to discover and comprehend the expected changes which will occur in the whole biosphere. Thus the dynamic water balance serves to protect nature.

It is impossible properly to understand the changes arising in biocoenosis without being familiar with the dynamics of water balance and vice-versa;

it is for example impossible to discern properly and understand the reasons for the encroachment by the steppe without knowing the changes which arose in the hydrosphere and as well as the secular changes, since these changes have already influenced man's activity for decades. In turn, the character of the changes which occur in biocoenosis, (the extinction of some species and appearance of new variants to replace the first), are symptoms and criteria of changes in the water balance. As the dynamic water balance is the basis for understanding transformations occurring in the world of plants and animals, so mutually confirmed changes in the quantitative and qualitative system of flora and fauna system bring about a readjustment of the historical water balance, in other words, of those relations prevailing before man's interference.

The reproduction of the water relations prevailing several hundreds of years ago, as well as inquiry into the changes arising in these relations up to the present, (or as we say today the reproduction of historic water balance), is, from the point of view of natural conservation, a very important task. Unfortunately, we have at our disposal a relatively insignificant quantity of sufficiently reliable data to allow us to develop this research on a larger basis.

9. Climate regulation

It is often pointed out that long periodical climatic changes are the reason for unfavourable changes arising in the hydric and biocoenotic system. However, we should here remember that we are dealing with changes with their background in the present, and not about secular climatic changes going back several centuries.

Climatological research conducted on the basis of data available from about the last 200 years and material from meteorological measurements do not indicate that, for the last 100 or 200 years, such changes occurred as to cause the transmutations observed in the world of plants and animals in some areas, chiefly those suffering from water deficiencies.

One reads a lot in scholarly literature and the press on the subject of the conscious and intentional change of climate by man. Our possibilities in this direction are limited and we are still unable to change climate. Through artificial mutations we attain only microclimatic and in most cases local climatic changes; the fact remains that we are unable to transform general climate. It may be that the atomic era will bring this effect with it. Up to now our influence on the climate takes place indirectly, through changes in water circulation and only to a small extent through changes in air current circulation in the atmospheric sphere near the earth.

In principle, each serious action pertaining to water economy indirectly influences to a lesser or greater degree local climate, or at least the microclimate, but such influence is not always advantageous. For instance, reserve reservoirs which store great water masses of considerable thermal inertia power, must influence the change in the surrounding areas temperature, thus softening climatic extremes and changing the humidity and heating of the adjacent earth. The same is true of other installations changing water circulation, (for instance, irrigation carried out an a large scale, soil drainage, river regulation and embankment are also in some way climate regulation). However, the influence of such operations on the microclimate is not always advantageous. Therefore the question of improving climate may

be honestly examined only in close connection with natural protection and preservation of equilibrated water balance.

The question also arises whether, in general, climate regulation is necessary in our country, and whether it would not be better to preserve such climate conditions as they naturally derive, even though they would not always be the best possible.

One may say that from the point of view of agricultural needs, climate regulation is indicated; namely to increase the average annual temperature, to abate the extremes and to raise spring temperatures, but may we be sure that this kind of change will not involve undesired transformations in the whole physiocoenotic, that is in the whole landscape?

Even under the assumption that, by such or another similar operation, we would be able to increase to some extent the air temperature in the vegetation period, we must note such a strong evaporation increase that we probably could, by no means, be capable of equilibrating it. To provoke precipitation in an artificial way, in order to avert unfavourable consequences is on a large scale, at the moment, out of the question.

Some climatologists (for instance dr Reichel) suppose the cause of the recently appearing water deficiencies in Central Europe to lie precisely in the increase of air temperature which took place in Europe during the last ten years.

On Polish territory we have observed some temperature rises, recorded by typical meteorological stations. This rise, in the course of a hundred years, did not exceed one degree; furthermore, it has not been established whether local natural changes, occurring in the vicinity of the observation station (for instance the building of a city, the cutting down of forests, and so on), do not lie at the origin of such a rise. However, should it be that there was established, without doubt, an actual rise in temperature, this would entail a heavy increase in evaporation with unfavourable repercussions for the water balance; in the areas with water balance barely equilibrated it could have a tremendous effect, leading directly to steppe encroachment.

It may be assumed that in Poland only problems of local climatic (rather microclimatic) regulation exist, such, for example, as protection against winds or combat against a water surplus or lack of humidity. Generally speaking, climatic regulation should in our country be directed, in principle, along lines of natural climatic preservation, i.e. maintaining its present proper character. Likewise, from the climatologic and hydrologic point of view the water economy should be directed so as to maintain the present state of affairs and not to worsen it.

If climate is to be healthy, whereby all characteristics of a natural landscape are preserved, the natural state of hydric and climatic relations are also to be maintained. Therefore, we have to adopt the water economy and climatic regulation to the general climate character and to natural hydrological relations. Three elements, i.e. climate, water relations and biocoenosis are so closely connected in their influence proceeding that the artificial change of any one of them would involve a change in the others, for the most part an undesirable one. The forest's clearing engenders a modification in water circulation as well as serious disturbances in the microclimate, or even the local climate.

Parana is an example where disadvantageous climatic changes have been caused by disastrous forest management, inasmuch as the excessive clearing of forests opened the way to cold South winds which affected the coffee

plantations climate very unfavourably. In certain years it occasions such losses in the coffee crop as to engender economic crises.

10. Physioactic tasks

The conception of natural preservation is a wider one than that of physioactic: it embraces not only the preservation of natural biocoenosic system and composite sites, but also the protection of an innate equilibrium as well as natural climatic relations.

Physioactic is a science which examines the ways of appropriate, artificial influence, in conformity with nature's rules, on the biocoenosis and biotop and the whole landscape, including the climate; all this is in accordance with the physiocoenosis type. It is a science which today is progressing and requires a fundamental elaboration of its research methods, but, only in the future, it should precisely become the base of our expanse planning.

If the water economy is to give a proper solution, not only in a technical sense, but also in relation to nature preservation requirements, it is necessary to tie together prospective water economy plans with physioactic, a science with a great future, one which provides the peculiar bases of an action, necessary to nature protection. Before we are able to speak about climatic changes and nature transformation, an attempt must be made to start from the elaboration of the physioactic bases applied to our physiocoenotic types. Unfortunately, in prospective plans, the necessary attention is still not paid to physioactic questions. This problem is often treated lightly, with a considerable dose of scientific ignorance. It happens so because physioactic conforms to varied academic disciplines, namely nature, geophysics (hydrology and meteorology), geography and technics. As could be expected in such a case, this discipline, being contiguous to others, remains for each of them a marginal question and does not find sufficient understanding. But with increasing interest and growing general comprehension of the necessity to protect nature, we may expect an appreciable improvement in this situation.

There is sufficient reason to assume that there will ensue a period in which natural perservation and rational management of resources will occupy the centre of interest in most civilized countries. Each more general principle will be checked by a physioactic principle. Geophysics, which treats only dead natural phenomena, will be connected with living nature and will serve her, by providing new opportunities for influencing physiocoenotic elements, in conformity with natural preservation needs. Then, projects aimed at maintaining a healthy natural state in nature, based on rational water regulation, consistent with the needs of biocoenosis, will become entirely genuine and more easily attained.

Warsaw, Poland, August 1959.

BEITRAG ZUR HYDROLOGISCHEN UND HYDROTECHNISCHEN VERWENDBARKEIT DER HOLZARTEN

ZD. VALEK, Tchécoslovaquie

ZUSAMMENFASSUNG

Die wasserwirtschaftliche Nützlichkeit der Pflanzenbestände in Quellgebieten besteht vor allem in der Aufhaltung der Niederschlagswässer im Bodenraum, Herabsetzung der Wasserverluste und des Bodenabtrages. Die Beobachtung des Gesamteinflusses des Landwirtschafts- oder Forstbetriebes im Gebiete auf die Wasserverhältnisse gibt kein klares Bild über die Ursachen einer größeren oder kleineren Wasserergiebigkeit eines Gebietes. Die Kontrolle der Beziehungen der spezifischen Formen und Eigenschaften der wachsenden Holzgewächse in ihrem Luft- und Bodenraum zum Niederschlag, zur Wasserspeicherung, bzw. zu den Standortsbedingungen im Raum der Uferlinie bietet einen sicheren Blick über die eigentliche Wirkung einzelner Holzarten und gibt eine gewisse Richtlinie für die Anwendung der Holzarten zu den hydrologischen und hydrotechnischen Aufgaben in den Quellgebieten.

Der Bericht befaßt sich mit den Ergebnissen einer 28jährigen Niederschlags- und Abflußmessung in einem bewaldeten und einem landwirtschaftlich bebauten kleinen Sammelgebiete und einer Kontrolle der Niederschlagsbewegung im Baumbereiche der Buche, Tanne und Fichte.

Im weiteren werden die Ergebnisse der Untersuchung der Verwendbarkeit der Laubholzarten zur Befestigung der Uferlinien mitgeteilt.

RÉSUMÉ

L'étude de l'influence hydrologique des forêts sur le bilan de l'eau dans le domaine des sources est introduite par la comparaison des quantités des précipitations et des débits écoulés de deux bassins dont l'un est complètement boisé et l'autre sans arbres.

I. EINLEITUNG

Den Anlaß zur Forschung auf dem Gebiete der hydrologischen und hydrotechnischen Verwendbarkeit der Holzarten in der Čechoslovakei haben einige Erfahrungen bei der Regelung der Gebirgsbäche gegeben. Zum großen Teile gebirgig, dicht bevölkert und von hoher Wirtschaftsintensität, ist unser ganzes Land empfindlich gegen Störungen, die die Hochwässer oder der Mangel an Wasser verursachen. Bauten von Stau- und Wasserleitungsanlagen, Flußkanalisierungen und andere wasserwirtschaftliche Bauvorhaben erfüllen zwar wichtige hydrotechnische Aufgaben, aber eine zielbewußte Sorge für das eigentliche Niederschlagswasser, seine Erhaltung im flüssigen Zustand, für die Ergiebigkeit der Wasserquellen, für Vorbeugungsmaßnahmen gegen Hochwasser im Gebirge hat sich bisher noch nicht entwickelt. Es gibt bei uns kein anderes Wasser als das, welches auf unser Gebiet in der Form von Niederschlägen fällt und das sich im flüssigen Zustand erhält. Den Forsten im Gebirge wird eine gewisse Wichtigkeit für die Wasserverhältnisse zuerkannt, aber der wirkliche Einfluß der einzelnen Holzarten auf das Wasserregime wurde vorläufig nicht in Betracht gezogen. Die großen Schwankungen des Wasserspiegels in den Wasserläufen und Brunnen waldloser Gebiete sind allgemein bekannt, aber der Einfluß der Wälder auf den Stand der Gewässer ist zahlreichen Erfahrungen gemäß nicht immer günstig.

Es fehlen die Kenntnisse über die tatsächlichen Einwirkungen der einzelnen Holzarten auf den Niederschlag und Abfluß, über die Verwendbarkeit der Holzgewächse für hydrologische und hydrotechnische Aufgaben, insbesonders über ihre Rückwirkung auf den Standort und auf das Wasserregime des Niederschlagsgebietes überhaupt. Nicht nur die Forstverwaltung, sondern auch der Forstdienstzweig, der in der Wasserwirtschaft tätig ist, hat hiefür keine festen Grundlagen. Im wesentlichen geht es um die Ausnützung der mächtigen und dauerhaften Körper der lebenden Holzgewächse zum Schutz des Bodens gegen Wassererosion und zwar nicht nur durch Verminderung des Oberflächenabflusses, sondern auch durch Befestigung der Bodenschichten mittels der festen Wurzeln, namentlich an schroffen Abhängen und Uferböschungen. Unmittelbare Ableitung der Regenwässer in den Boden bedeutet eine Verminderung der physikalischen Verdunstung, der das Regenwasser an der Erdoberfläche ausgesetzt ist.

Es fehlt aber nicht an Beispielen einer Verbesserung, bzw. auch Verschlechterung der Ergiebigkeit der Wasserquellen infolge Aufforstung des Sammelgebietes. Die gleichen Folgen kann auch eine Abholzung verursachen. Diese Widersprüche in den Kenntnissen über die Einwirkungen der Wälder auf die Wasserverhältnisse in den Sammelgebieten hatten zur Folge, daß in der Waldwirtschaft nur die Holzproduktion gefördert wurde und den wasserwirtschaftlichen Bedürfnissen, besonders in den Quellgebieten, sowie auch der Wahl der Holzarten und der Art der Bewirtschaftung nicht die gebührende Aufmerksamkeit gewidmet wurde. Die Wassererosion bedeutet nicht nur eine Beschädigung des Bodens, sondern auch die Störung des Wasserhaushaltes. Jeder Hohlraum im Boden oder ein natürlicher bzw. künstlicher Einschnitt in denselben oder eine Erosionsrinne bedeutet vor allem eine Bodenentwässerung, da die infiltrierten Niederschlagswässer zutage treten und die natürlichen Wasserreserven Einbuße erleiden. In den Wasserläufen deponierte Geschiebemassen, gleichgültig, ob sie in entlegenen Gebieten oder in den nächsten entstanden sind, stören das Gleichgewicht des ganzen Abflußregimes. Die Geschiebebänke verursachen am Ort der Auflagerung neue Quer- und Längserosionswirkungen in den Gerinnen. In den Unterlaufstrecken, wo das Geschiebe das Gerinne vollgefüllt hat, kommt es zu Überschwemmungen und Vernässungen der Grundstücke, was vom hydrologischen Standpunkt große Wasserverluste bedeutet.

Die Regulierung der zerstörten Wasserlaufstrecken bedeutet keineswegs eine dauerhafte Abhilfe gegen solche Übel. Eine große Anzahl von Bauvorhaben, Schutzbauten an den zerstörten Strecken der Wildbäche in den Karpaten, Beskiden, im Riesengebirge und in anderen Gebieten, welche in den Jahren 1920—1955 vom Hochwasser heimgesucht wurden, haben dies von neuem bestätigt.

Der Zustand der Quellstrecken der Bäche ist abhängig von den hydrologischen Verhältnissen in den Sammelgebieten. Der Zustand der Flüsse ist von den hydrologischen Verhältnissen der Zuzüge abhängig. Störungen in der Entwicklung der Flußgerinne werden durch Anhäufung von solchen Erscheinungen in den oberen Strecken verursacht. Kostspielige Wasserbauten zur Behebung der Hochwasserschäden waren manchmal nicht rentabel, auch wenn sie auf das Notwendigste beschränkt wurden. Die Anwendung von Laubholzarten zur Befestigung von mehr als zehnmal längeren Uferabschnitten wäre manchmal viel billiger und dauerhafter.

Eine gut organisierte Wasserwirtschaft sollte nicht ihre Wasserquellen, d. s. die Niederschlagswässer an den Stellen des häufigsten Vorkommens, im Gebirge, dem Schicksal überlassen. Die Bedingungen für die Erhaltung des

höchsten Anteiles der Niederschläge im flüssigen Zustand entsprechen nicht den heutigen Ansprüchen an Wasser.

Wie zu diesen hydrologischen und hydrotechnischen Aufgaben unsere Holzarten anwendbar sind, haben die Ergebnisse der Forschungsarbeiten, die in den Jahren 1928—1951 im Ministerium für Landwirtschaft und in den Jahren 1952—1955 in der wasserwirtschaftlichen Forschungsanstalt in Prag durchgeführt wurden, beigetragen.

II. Die Forschung

Die Forschung auf dem Gebiete der hydrologischen Wirkungen des Waldes auf den Wasserhaushalt in Quellgebieten wurde eingeleitet auf Grund einer Vergleichung der Niederschlags- und Abflußmengen in zwei Sammelgebieten, von welchen das eine voll bewaldet ist (Kychová, Gemeinde Huslenky, Bez. Vsetín, Lage 18°09'28"—18°11'16" östl. von Greenwich und 49°16'10"—49°17'16" nördl. Breite), während das zweite ein waldloses Gebiet ist (Zdechovka, Gemeinde Zdechov, Bez. Vsetín, Lage 18°03'20"—18°05'38" östl. von Greenwich und 49°14'29"—49°16'07" nördl. Breite) und landwirtschaftlich genutzt wird.

Beschreibung der Forschungsgebiete

Das bewaldete Gebiet Kychová mißt 4,27 km^2 (das waldlose Gebiet 4,09 km^2) und liegt in einer Seehöhe von 556—923 m (das waldlose Gebiet 482—783 m); die mittlere Höhe des Gebietes beträgt 727 m ü. M. (des waldlosen Gebiets 623 m). Die durchschnittliche Neigung der Abhänge beträgt 31 v. H. (des waldlosen Gebiets 25 v. H.). 91 v. H. des Geländes liegt in einer Höhe zwischen 600—850 m (des waldlosen Gebiets zwischen 500—750 m 98 v. H.). Das bewaldete Gebiet ist gegen Westen (das waldlose Gebiet gegen Norden) orientiert.

Geologische Verhältnisse

Beide Gebiete liegen in einem Streifen von gleichen paleogennen Schichten. Der Felsuntergrund wird von zwei Schichten gebildet und zwar von einer Schicht des Karpatensandsteines und der hieroglyphischen Schichten. Im bewaldeten Gebiet haben die Karpatensandsteine eine Ausdehnung von 12 v. H. (im waldlosen Gebiet 6 v. H.), die hieroglyphischen Schichten betragen 88 v. H. (im waldlosen Gebiet 94 v. H.). Die hieroglyphischen Schichten sind für Wasser undurchlässig und das Niederschlagswasser kann nur in eine verwitterte Oberschicht eindringen. Karpatensandsteine sind an der Oberfläche zersprengt und die Spalten reichen in eine Tiefe von 2—7 m. Die orographischen Wasserscheiden stimmen mit den Infiltrationswasserscheiden überein.

Die Böden in beiden Gebieten sind vorwiegend lehmig. Das Erdreich mit einer felsigen Unterlage in der Tiefe von 20—60 cm beträgt im bewaldeten Gebiet 60 v. H. der Gesamtfläche, im waldlosen Gebiet 7 v. H.

Witterungs- und Abflußverhältnisse

Der durchschnittliche Jahresniederschlag (XII.—XI.) im bewaldeten Gebiet beträgt 997 mm, im waldlosen Gebiet 889 mm. Die durchschnittliche Anzahl der Niederschlagstage im bewaldeten Gebiet ist 113, im waldlosen Gebiet 111.

Der größte Tagesniederschlag im bewaldeten Gebiet betrug 90,7 mm, im waldlosen Gebiet 91,7 mm. Der längste niederschlagslose Zeitraum dauerte 45 Tage (im Jahre 1943). Die durchschnittliche Tagestemperatur war im bewaldeten Gebiet 6,1 ° C, im waldlosen Gebiet 6,4 ° C; die Tagesmaxima haben bis 32—34 ° C erreicht, das absolute Minimum war —35,6 ° C (11. 2. 1929). Die durchschnittliche Dauer der Schneedecke beträgt im bewaldeten Gebiet 92 Tage, im waldlosen Gebiet 85 Tage. In den Monaten November—April fielen durchschnittlich im bewaldeten Gebiet 42 v. H., im waldlosen Gebiet 63 v. H. Die durchschnittliche Jahresabflußhöhe, die im bewaldeten Gebiet am Meßüberfall festgestellt wurde, maß 472 mm, d. s. 47 v. H.; durch die Wasserleitungsanlage wurde dem bewaldeten Gebiet jährlich weitere 173 mm entnommen. Im waldlosen Gebiet maß die durchschnittliche Jahresabflußhöhe 482 mm, d. s. 53 v. H.

Bewaldetes Gebiet

Von der Gesamtfläche des bewaldeten Gebietes 4,27 km² entfällt auf Hutweiden, Wiesen und Ackerfelder 3,8 v. H., auf Bauflächen, Wege und Wasserläufe 0,8 v. H. und auf Waldungen, einschließlich der Waldwege 95,0 v. H. Die Waldbestände sind als Hochwald im Plenterbetrieb bewirtschaftet. Die durchschnittliche Umtriebszeit beträgt 100 Jahre, der jährliche schlagbare Zuwachs ist 6,7 fm/ha. Auf die Buche (Fagus silvatica) entfällt eine Fläche von 151,55 ha, d. s. 37,2 v. H., auf die Tanne (Abies pectinata) 111,33 ha, d. s. 27,4 v. H., auf die Fichte (Picea excelsa) 110,66 ha, d. s. 27,2 v. H., auf den Bergahorn (Acer pseudoplatanus) 29,36 ha, d. s. 7,2 v. H. und der Rest, d. s. 4,5 ha oder 1,0 v. H., nimmt die Lärche (Larix europeus), Eberesche (Sorbus aucuparia), Esche (Fraxinus excelsior) und Linde (Tilia cordata) ein. Die Laubhölzer sind mit 45 v. H. vertreten. Die genannten Holzarten kommen nur in Mischbeständen vor.

Der Hauptwasserlauf im bewaldeten Gebiet, der Kychovábach, gliedert das Gebiet in zwei Teile; der Nordabhang ist kürzer (0,8—1,0 km) und die Zuzüge haben größere Gefälle (12—28 v. H.) als die vom südlichen Abhang (11—18 v. H.), der länger ist (1,2—1,8 km). Der Hauptbach hat vorwiegend ein seichtes Gerinne (0,5—1,0 m Tiefe), seine Breite ist ungefähr 2,0—3,0 m. Das Sohlengefälle beträgt 8,0 v. H. Die Sohle und die Ufer sind gut erhalten. 4 rechtsseitige und 4 linksseitige Zuzüge teilen das Gebiet in 8 Seitentäler ein. Infolge der erhöhten Holznutzungen und der Verwendung der Gerinne zum Erdriesentransport kam es zu großen Ufer- und Sohlenbeschädigungen, womit große Schuttmengen frei gemacht werden.

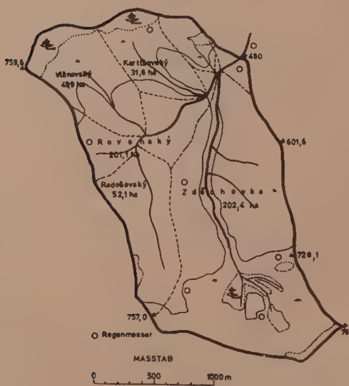
Der Talweg ist als Waldstraße ausgebaut; 21 km der Waldwege werden nicht erhalten und dienen teilweise als Erdriesen für den Holztransport.

Vom oberen Teil des Sammelgebietes des linksseitigen Zuzuges Lukašice (Fläche 0,7 km²) wird durch eine Tiefdrainage (3—10 m Tiefe) das Wasser für eine Gruppenwasserleitung entzogen.

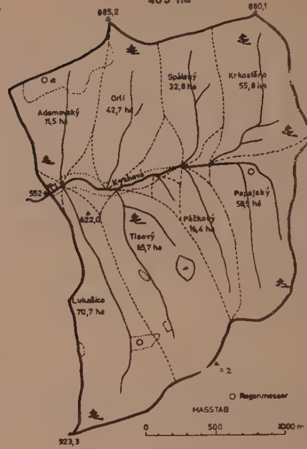
Waldloses Gebiet

Von der Gesamtfläche des waldlosen Gebietes Zdechovka, 4,09 km², entfallen auf die Hutweiden 39,9 v. H., auf Felder 44,7 v. H., auf Wiesen und Gärten 7,6 v. H., auf Waldungen 4,6 v. H. und auf Bauflächen, Wege und Wasserläufe 3,2 v. H. Die landwirtschaftlichen Kulturen nehmen 92 v. H. der Gesamtfläche ein, die Waldungen 4,6 v. H.

KARTE DES NIEDERSCHLAGSGEBIETES
DES ZDĚCHOVKABACHES
404 ha



KARTE DES NIEDERSCHLAGSGEBIETES
DES KYCHOVÁBACHES
409 ha



Die Hutweiden sind nicht gepflegt und befinden sich nur in steilen Lagen mit seichten Bodenschichten; die Grasbestände sind lückenhaft und stellenweise durch den Verkehr so zerstört, daß sie allmählich in Schotterfelder umgewandelt werden. Um den Ackerbau zu erleichtern sind die Abhänge terrassiert worden. Von Getreidearten werden auf den Feldern Korn, Weizen, Hafer und Gerste, dann Buchweizen, von den Futtermitteln Rotklee und von Hackfrüchten Kartoffeln, Futterrüben und Kraut angebaut. Die Waldungen bestehen aus 8 Fichtenbeständen mit eingesprengten Kiefern und Buchen.

Als Hauptwasserlauf im waldlosen Gebiet gilt der Rovenskybach, der in der Richtung der Hieroglyphenschichten läuft. Der Nordabhang ist kürzer (0,8—1,0 km) und wird von 3 Zuzügen entwässert, der Südabhang ist länger (1,58—2,55 km) und wird von 2 Zuzügen entwässert. Der erste rechtsseitige Zuzug, Zdechovkabach, ist der längste und wasserreichste Wasserlauf in diesem Gebiet; sein Bachbett zeigt Spuren von heftigen Wasserangriffen. Es ist stellenweise bis auf 12 m in die Ausläufe der Hieroglyphenschichten der Talsohle eingeschnitten. Im Quellgebiet dieses Zuzuges sind tiefe Runsen ausgewaschen. Die Vertiefung des Zdechovkabaches hat eine dauernde beiderseitige Hangrutschung hervorgerufen. Der Hauptbach Rovensky hat in einer Länge von 270 m ebenfalls ein angegriffenes Bachbett; im weiteren Verlauf ist sein Bachbett infolge der neuen Ablagerungen von angeschwemmtem Erdreich wesentlich kleiner.

Die Länge der Feldwege, bloß im Gebiet des Zdechovkabaches, mißt 22 km (Gefälle bis 22 v. H.); sie konzentrieren die Abflußmengen schneller als die Bäche.

Zusammenfassung

Im Zustand der beiden Versuchsgebiete sind Unterschiede, wie aus der Beschreibung zu ersehen ist. Die Anwendung einer Vergleichsmethodik für die Verwertung der Einflüsse der Waldbestände und der landwirtschaftlichen

Kulturen auf das Wasserregime in Quellgebieten ist berechtigt unter der Voraussetzung, daß die Gebiete sich nur durch die Kulturart unterscheiden. Der Hauptforderung, daß die Gebiete gleichen geologischen Verhältnissen angehören, wurde durch eine entsprechende Wahl der Objekte Folge geleistet. Eine gewisse unsymmetrische Verteilung der Längen- und Gefällsverhältnisse hat einen rascheren Abfluß im bewaldeten Gebiet zur Folge. In Wirklichkeit ist der Abfluß im waldlosen Gebiet rascher. Die schwächere Bodenschicht sollte im Waldgebiet eine geringere Grundwasserbildung als im waldlosen Gebiet zur Folge haben. Die Messungen der kleinsten Abflußmengen während der regenlosen Perioden haben im bewaldeten Gebiet eine größere Grundwasserergiebigkeit nachgewiesen. An kahlen, den Winden ausgesetzten Abhängen im waldlosen Gebiet wurden kleinere Niederschlagsmengen gemessen als es der Wirklichkeit entspricht. Es ist nicht gelungen, diesen Mangel bei der Niederschlagsmessung zu beseitigen, aber die Zahlenwerte wurden nicht korrigiert.

Forschungsergebnisse

Die Ergebnisse der 28jährigen Beobachtungen der Niederschlags-, Abfluß- und Bodenverhältnisse und der Art der Bodennutzung haben deutlich einen klaren Unterschied in der Beschaffenheit und Größe der Abflußmengen nachgewiesen. Die Pflanzenbestände in diesen Gebieten treffen nicht mit ihren ober- und unterirdischen Teilen in gleicher Reichweite die Bahn der Niederschläge in ihrem Luft- und Bodenraum und äußern sich, in Verbindung mit der Technik der Bodenbewirtschaftung, als ein eigenartiger Faktor des Wasserregimes eines Quellgebietes. Die Reichweite ist bedingt durch die Größe, Form und Widerstandsfähigkeit des Pflanzenkörpers. Sie ist ein spezifisches Zeichen der Lebensbeziehungen der einzelnen Pflanzenarten zur Umwelt.

Die Bearbeitung der Ergebnisse wurde in 3 Kapitel eingeteilt:

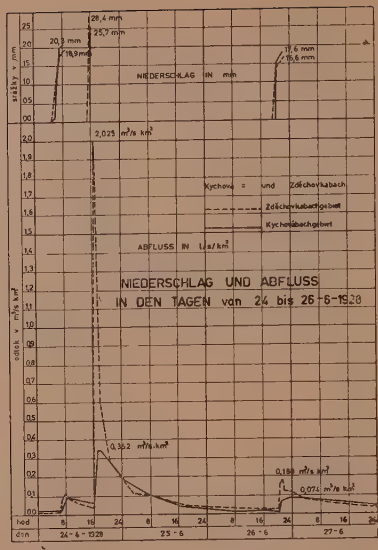
Regime der Hoch- und Schneewässer

In den Jahren 1928—1955 wurden im bewaldeten Gebiet in 169 und im waldlosen Gebiet in 233 Fällen spezifische Abflüsse gemessen, die mehr als 100 l/sek./km² betrugen. Die charakteristischen Fälle sind in der Beilage graphisch dargestellt, einige hier beschrieben.

a) Niederschlag und Abfluß am 24. Juni 1928 (Abb. S. 328)

Im regenreichen Monat, als das bewaldete Gebiet noch unter dem Einfluß der Schneeschmelze stand, sind am 24. Juni 1928 zwei kurze Gußregen niedergegangen. Im bewaldeten Gebiet fiel in der Zeit von 6.00—9.00 Uhr im ganzen 19,3 mm, im waldlosen Gebiet in der Zeit von 5.45—6.40 Uhr 15,6 mm. Im bewaldeten Gebiet kulminierte der Abfluß um 8.40 Uhr mit 88 l/sek./km², im waldlosen Gebiet um 7.45 Uhr mit 118 l/sek./km². Der Nachmittagsregen begann im bewaldeten Gebiet um 16.00 Uhr und bis 16.30 Uhr fiel 25,7 mm (davon 25,0 mm, $i = 1,66$ mm/min.); nach 50' ist der Abfluß auf einen Höchstwert von 354 l/sek./km² gestiegen. Im waldlosen Gebiet begann es um 15.30 Uhr zu regnen, und es wurde eine Niederschlagsmenge von 28,4 mm (davon 25,7 mm, $i = 1,03$ mm/min.) gemessen. Der Abfluß begann um 16.00 Uhr zu steigen und um 16.35 Uhr erreichte er ein Maximum von 2025 l/sek./km².

Der Abflußmengezuwachs der steigenden Flutwelle in einer Minute, den ich als Abflußintensität (I) bezeichne, betrug während des Nachmittagsregens



im bewaldeten Gebiet (354 — 54 l/sek./km², d. s. 300 : 50') = 6 l/min./km², im waldlosen Gebiet (2025 — 39 l/sek./km², d. s. 1986 : 35') = 56 l/min./km², d. h. er war mehr als neunmal größer. Im waldlosen Gebiet hat die Flutwelle 630 m³ Geschiebe mitgebracht.

b) Niederschlag und Abfluß in den Tagen vom 15. bis 17. IX. 1938 (Abb. S. 329)

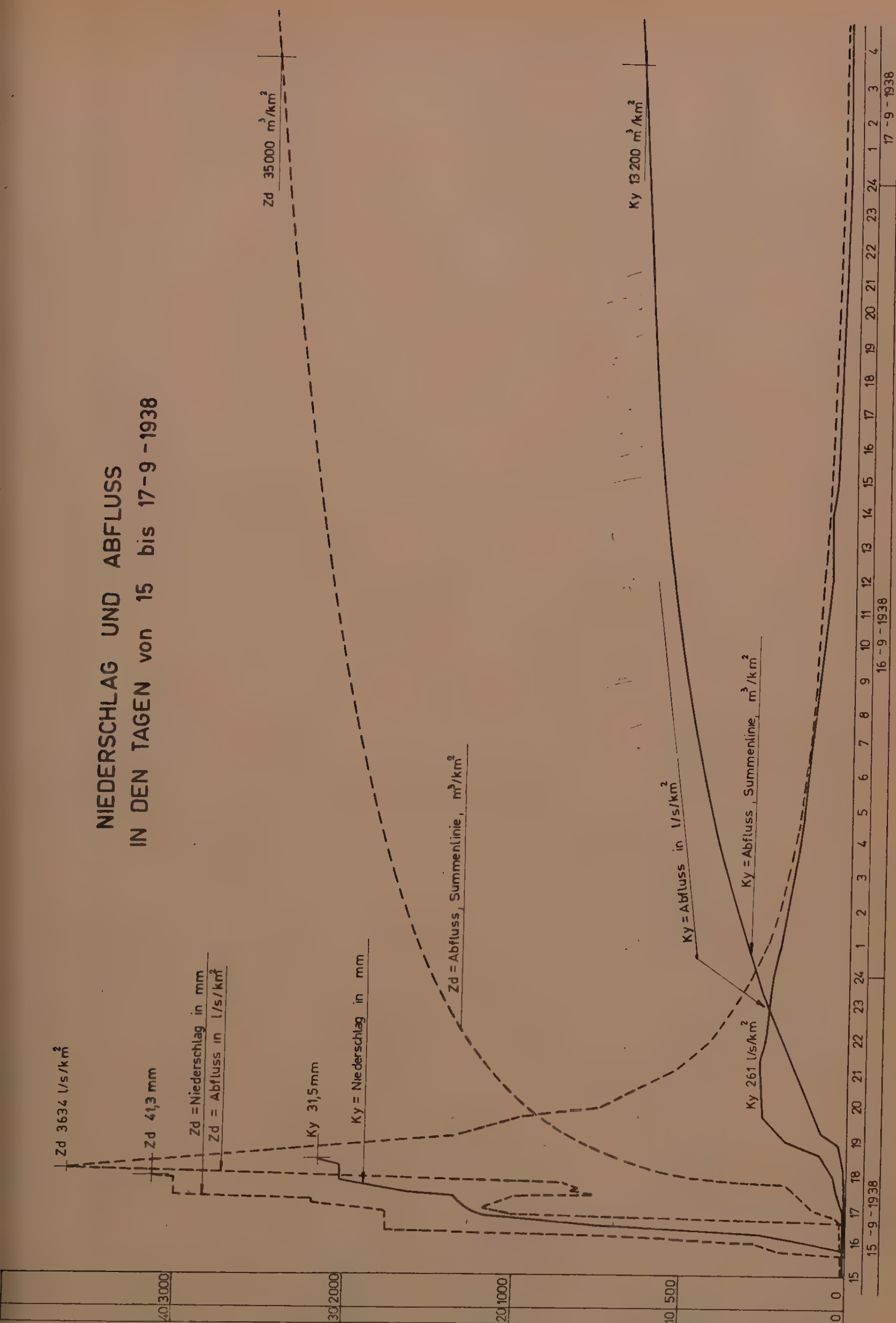
In diesem Zeitraum kam es zur größten spezifischen Abflußmenge im waldlosen Gebiet. Die Niederschlagshöhe betrug 41,3 mm (Niederschlagskern 15,4 mm, i = 1,2 mm/min.). Der Höchstabfluß erreichte 3634 l/sek./km² (I = 112 l/min./km²). Von den Niederschlägen am 15.—19. IX. 1938 im waldlosen Gebiet in der Höhe von 56,7 mm sind 25 437 m³/km², d. s. 90 v. H. abgeflossen.

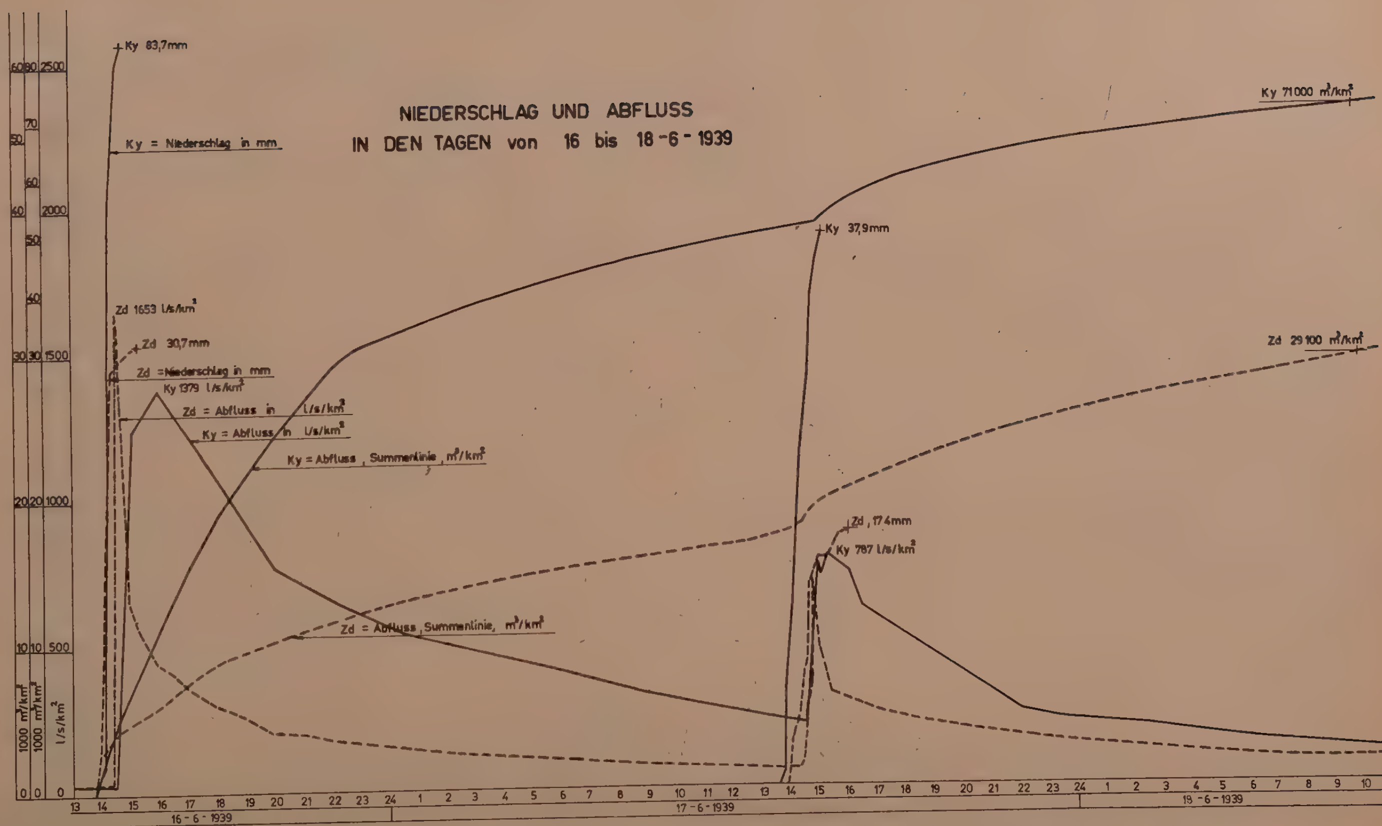
c) Niederschlag und Abfluß in den Tagen vom 16. bis 18. VI. 1939 (Abb. S. 330)

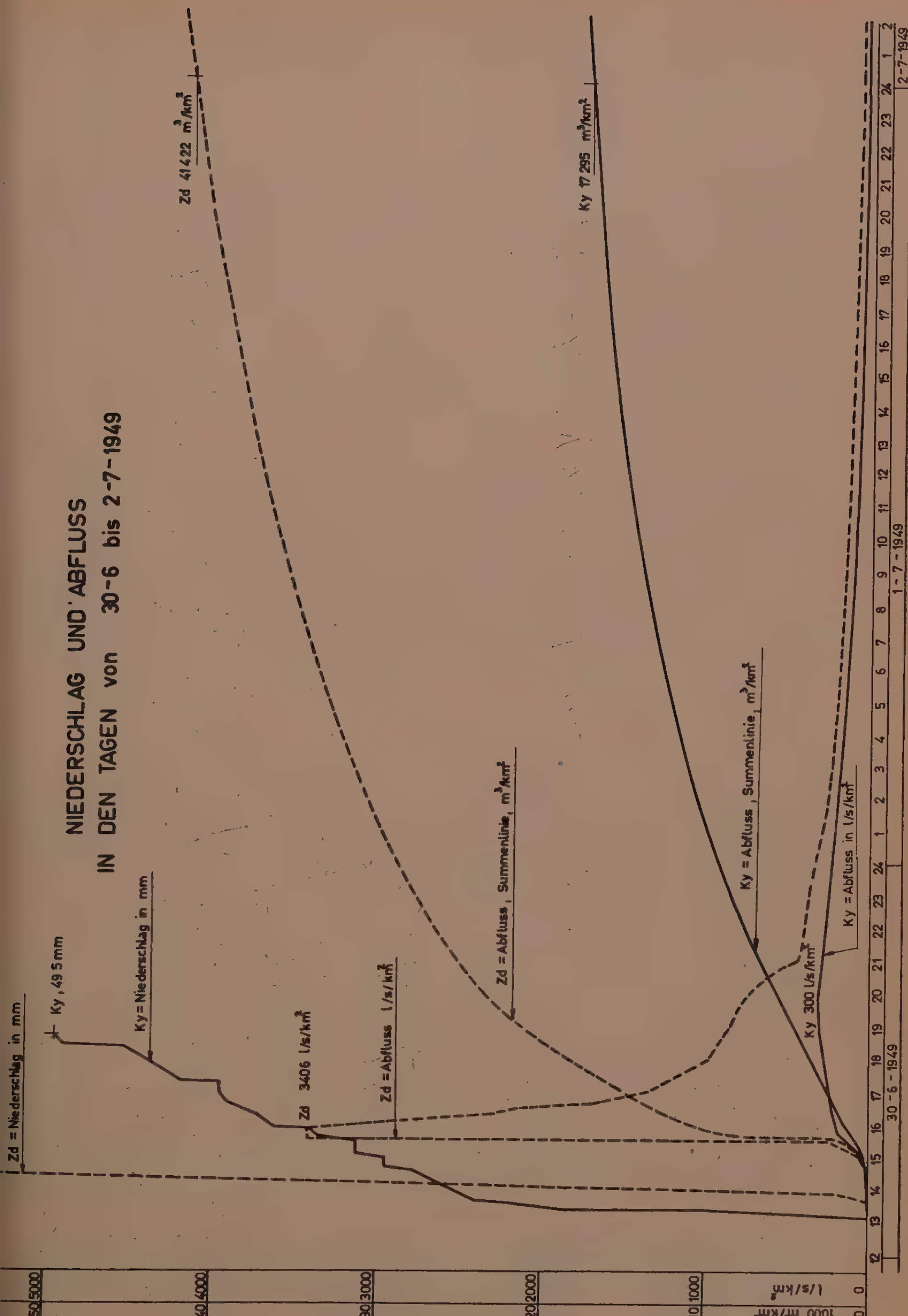
In dieser Zeit wurde die höchste spezifische Abflußmenge im bewaldeten Gebiet gemessen. Der Niederschlag am 16. VI. 1939 dauerte von 13.45 bis 14.50 Uhr und betrug 63,7 mm (Niederschlagskern, 34,5 mm, i = 3,8 mm/min.), die spezifische Abflußmenge wurde mit 1379 l/sek./km², I = 35 l/min./km² gemessen. Im waldlosen Gebiet dauerte der Niederschlag von 13.45 bis 15.20 Uhr und betrug 30,7 mm (Niederschlagskern 14.00—14.10 Uhr, 18,5 mm, i = 1,85 mm/min.), die spezifische Höchstabflußmenge erreichte 1635 l/sek./km², I = 325 l/min./km².

d) Niederschlag und Abfluß in den Tagen vom 18. bis 23. VII. 1949

Ein 25 Stunden dauernder Regen im bewaldeten Gebiet hatte eine Höhe von 90,7 mm erreicht (im waldlosen Gebiet 91,7 mm in 31 Stunden). Der Kulminationsabfluß im bewaldeten Gebiet stieg auf 621 l/sek./km², im wald-


NIEDERSCHLAG UND ABFLUSS
IN DEN TAGEN von 15 bis 17-9-1938
Zd 3634 l/s/km²
Zd 41,3 mm
Zd = Niederschlag in mm
Zd = Abfluss in l/s/km²
Ky 31,5 mm
Ky = Niederschlag in mm
Zd = Abfluss, Summenlinie, m³/km²
Ky 261 l/s/km²
Ky = Abfluss in l/s/km²
Ky = Abfluss, Summenlinie, m³/km²
Zd 35000 m³/km²
Ky 13200 m³/km²
15-9-1938
16-9-1938
17-9-1938


NIEDERSCHLAG UND ABFLUSS
IN DEN TAGEN von 16 bis 18-6-1939
Ky 83,7mm
Ky = Niederschlag in mm
Zd 1653 l/s/km²
Zd 30,7mm
Zd = Niederschlag in mm
Ky 1379 l/s/km²
Zd = Abfluss in l/s/km²
Ky = Abfluss in l/s/km²
Ky = Abfluss, Summenlinie, m³/km²
Zd = Abfluss, Summenlinie, m³/km²
Ky 37,9mm
Zd, 17,4mm
Ky 787 l/s/km²
Ky 71000 m³/km²
Zd 29100 m³/km²
1000 m³/km²
1000 m³/km²
l/s/km²
16-6-1939
17-6-1939
18-6-1939


NIEDERSCHLAG UND ABFLUSS
IN DEN TAGEN von 30-6 bis 2-7-1949
Zd = Niederschlag in mm
Ky , 49.5 mm
Ky = Niederschlag in mm
Zd 3406 l/s/km²
Zd = Abfluss l/s/km²
Zd = Abfluss , Summenlinie, m³/km²
Zd 41422 m³/km²
Ky 17295 m³/km²
Ky = Abfluss , Summenlinie, m³/km²
Ky 300 l/s/km²
Ky = Abfluss in l/s/km²
30-6-1949
1-7-1949
2-7-1949
l/s/km²
1000 m³/km²

losen Gebiet auf 1163 l/sek./km². Vom Gesamtniederschlag 120,3 mm in den Tagen vom 18. bis 23. VII. 1949 sind 79 261 m³/km² abgeflossen, d. s. 66 v. H. (im waldlosen Gebiet betrug der Niederschlag 111,3 mm, der Abfluß 90 525 m³/km², d. s. 81 v. H.).

e) Schneewasserabfluß im Jahre 1932

Die Schneeschmelze in der Zeit vom 30. III. bis 8. IV. 1932 wurde durch einen warmen Südwind hervorgerufen. Die Tageslufttemperatur stieg im waldlosen Gebiet bis 17 ° C, im bewaldeten Gebiet bis 15 ° C. Der Wasserwert der Schneeschicht im bewaldeten Gebiet betrug 99 mm, im waldlosen 58 mm. Die spez. Höchstabflußmenge erreichte im bewaldeten Gebiet 254 l/sek./km², I = 0,39 l/min./km², im waldlosen Gebiet 342 l/sek./km², I = 0,94 l/min./km².

In der Winterperiode vom 1. XII. bis 30. IV. 1932 fielen im bewaldeten Gebiet 258,7 mm der Niederschläge, wovon 203 mm, d. s. 78 v. H. abgeflossen sind, im waldlosen Gebiet betrug der Niederschlag 196,5 mm, der Abfluß 198 mm, d. s. 101 v. H.

f) Schneewasserabfluß im Jahre 1949

Die Schneeschmelze (23. III. bis 30. IV.) wurde durch eine starke Sonnenstrahlung hervorgerufen. Der Wasserwert der Schneeschicht im bewaldeten Gebiet betrug 184 mm, im waldlosen Gebiet 146 mm. Die Abflußintensität im bewaldeten Gebiet erreichte einen Wert von 0,5—0,33 l/min./km², im waldlosen Gebiet von 0,42—0,66 l/min./km², wobei sich die Schneeschmelze bis Ende Mai verlängerte. Vom Niederschlag in der Höhe 520,2 mm in den Monaten XII.—V. sind im bewaldeten Gebiet 399 mm abgeflossen, d. s. 77 v. H., im waldlosen Gebiet betrug der Niederschlag 419,1 mm, der Abfluß 378 mm, d. s. 90 v. H.

Zusammenfassung

Die Frage, ob die Waldbestände die Hochwasserfluten und ihre Wirkungen vergrößern oder vermindern, haben die Ergebnisse der 28jährigen Messungen der Niederschläge und Abflüsse im bewaldeten und im waldlosen Gebiet klar beantwortet. Die Mischbestände von Buche, Tanne und Fichte im Kychovágebiet verzögern wesentlich die Niederschlagswasserkonzentration und vermindern die Abflußintensität.

In den Jahren 1928—1955 wurden im bewaldeten Gebiet 132 Fälle spezifischer Abflüsse von 100—299 l/sek./km² verzeichnet (im waldlosen Gebiet 159), 27 Fälle spez. Abflüsse von 300—499 l/sek./km² (im waldlosen Gebiet 44), 8 Abflüsse von 500—999 l/sek./km² (im waldlosen Gebiet 23) und 2 Fälle größerer Abflüsse als 1000 l/sek./km² (im waldlosen Gebiet 7 Fälle).

Die Geschwindigkeit, mit welcher sich die Niederschlagswässer konzentrieren und die Größe des Abflußmengenzuwachses der steigenden Flutwelle in l/min./km² ausgedrückt, sind ein verläßlicher Vergleichsmaßstab. Die größte Abflußintensität im bewaldeten Gebiet von 35 l/min./km² wurde bei dem maximalen spez. Abfluß von 1379 l/sek./km² beobachtet (Niederschlagsintensität bis 3,8 mm/min.). In allen anderen Fällen der höheren Abflüsse war die Abflußintensität nicht größer als 7 l/min./km². Im waldlosen Gebiet betrug der Höchstwert der Abflußintensität 635 l/min./km² (spez. Abfluß 3406 l/sek./km²), die weiteren Höchstwerte waren 325, 112, 73 l/min./km², also wesentlich höher als im bewaldeten Gebiet, trotzdem die Beschaffenheit des bewaldeten Gebietes einen schnelleren Abfluß ermöglichte.

Eine lehrreiche Vergleichung der Abflußverhältnisse in beiden Gebieten ermöglichten die Querprofile des Kychová- und Zdechovkabaches in den Abschnitten, in welchen die Meßobjekte im Jahre 1927 ausgebaut wurden (Gebietsflächen à 4 km²). Im bewaldeten Gebiet war am Kychovábach das Profil am km 5,83, wo der Meßüberfall errichtet wurde, 0,8 m tief, in der Sohle 2,3 m breit (Gefälle 3,8 v. H.); seine Querfläche betrug 3 m². Im waldlosen Gebiet war am Zdechovkabach am km 4,7 ein 2,6 m tiefes, in der Sohle 7 m breites, stark erodiertes Gerinne von einer Querfläche von 37 m² entstanden. Der Stand des Bachgerinnes im bewaldeten Gebiet ist ein Beweis dessen, daß auch in der weiten Vergangenheit dort keine so schädlichen Hochwässer zu verzeichnen waren, wie es sich im waldlosen Gebiet ereignet hat.

Trockenperioden

In den Jahren 1928—1955 sind 37 Fälle der Trockenperiode beobachtet worden. Als solche Fälle werden Tagesreihen betrachtet, an denen in einem von beiden Versuchsgebieten der durchschnittliche Tagesabfluß unter 1 l/sek./km² gesunken ist. Im Sommerhalbjahr sind es 8 bzw. mehr regenlose Tage oder Tage mit so kleinen Niederschlägen, daß sie den Oberflächenabfluß nicht beeinflussen. In der Winterzeit sind es außerdem noch die Frostperioden. Die Dauer der Trockenperioden betrug 1322 Tage; der durchschnittliche Tagesabfluß im bewaldeten Gebiet war 1,21 l/sek./km², im waldlosen Gebiet 0,78 l/sek./km². In 7 Fällen war der durchschnittliche Tagesabfluß im waldlosen Gebiet um 0,1—0,63 l/sek./km² höher als im bewaldeten Gebiet; in 2 Fällen ist er im waldlosen Gebiet auf 0,02 l/sek./km², in 26 Tagen auf 0,03—0,10 l/sek./km² und in 66 Tagen auf 0,11—0,22 l/sek./km² gesunken. Der niedrigste durchschnittliche Tagesabfluß wurde im bewaldeten Gebiet auf dem Meßüberfall mit 0,22 l/sek./km² festgestellt. Die Charakteristik der Grundwasserverhältnisse des bewaldeten Gebietes wird noch präsentiert durch die Angabe der Wassermengen, die durch die Wasserleitungsanlage aus dem Sammelgebiet des linksseitigen Zuzuges Lukašice (0,7 km²) entzogen werden; der niedrigste durchschnittliche Grundwasserabfluß von 1,0 l/sek. bedeutet einen wesentlich höheren Wasserreichtum als dies im waldlosen Gebiet der Fall ist, wo in Trockenperioden die bis 8 m tiefen Brunnen austrocknen und im Quellgebiet sich ein Mangel an Wasser bemerkbar macht.

Die Mischbestände der Buche, Tanne und Fichte erhöhen das Wasserspeicherungsvermögen der Bodenschicht im bewaldeten Gebiet und dadurch auch die Ergiebigkeit der Quellen in den Trockenperioden.

Einfluß der Kraut- und Holzgewächse auf die Niederschlagswasserbewegung durch ihren Luft- und Bodenraum

Im waldlosen Gebiet beeinflussen die landwirtschaftlichen Kulturen den Luftraum in einer durchschnittlichen Höhe von 28 cm für die Dauer von ca. 160 Tagen. In der übrigen Wachstumszeit, d. s. ungefähr 70 Tage, mißt die durchschnittliche Höhe der Pflanzendecke 2,0—12,0 cm und nach 200 Tagen hat die lebendige Bodendecke keine praktische Bedeutung für die Wasseraufnahme. Die Bodenschicht wird mit dem Wurzelwerk vom 1. V. bis 15. VIII., d. s. 100 Tage, in einer durchschnittlichen Tiefe von 15 cm, in der übrigen Zeit in einer Tiefe von 8 cm beeinflußt.

Im bewaldeten Gebiet wird der Luftweg der Niederschläge im Kronenraum in einer Schicht von der durchschnittlichen Höhe 17 m und der Bodenraum in einer Tiefe von 0,85 m betroffen.

Die schwachen, weichen und nachgiebigen Körper der Krautgewächse, sei es im dichten oder dünnen Verband, sind nicht im Stande den ober- oder unterirdischen Weg der Niederschläge zu beeinflussen oder eine abschüssige Bodenfläche so zu befestigen, wie es die festen, dauerhaften und tief im Boden mit festen und dichten Wurzeln festgeankerten Holzarten im Stande sind.

Interzeption der Niederschläge

Bis jetzt ist es nicht gelungen, eine praktische Art der Messung der Wassermengen, die an den oberirdischen Teilen der Gewächse während des Regens haften bleiben, zu finden; deswegen wurde die Interzeption an den Gewächsen nicht gemessen. Die Interzeption an den Hauptholzarten, die im bewaldten Gebiet vorkommen, wurde an Buchen, Fichten und Tannen in je zwei Altersklassen gemessen. Es wurden typische Bestände nach dem Alter, Verband und Kronenschluß gewählt. Die Meßeinrichtungen bestanden aus normalen Regenmessern, die mit einem Fanggefäß von 2500 cm² Fläche ausgestattet wurden, wobei auf eine Versuchsfläche von 1 Ar 7500 cm² der Fangflächen entfielen. Das an den Baumstämmen herabfließende Wasser wurde mit einem Dachpappering gefaßt und mit einem Gummischlauch in ein Gefäß abgeleitet.

Nach den Ergebnissen der dreijährigen Messungen in den Buchenbeständen gelangt durchschnittlich 90 v. H. der jährlichen Niederschläge zum Boden, in den Tannenbeständen durchschnittlich 81 v. H. und in den Fichtenbeständen durchschnittlich 60 v. H. Die Niederschlagswassermenge, die an den Bäumen festgehalten wird, hängt vom Verband, Kronenschluß sowie von der Lage und von der Biegsamkeit der Äste ab. Im Mittelgebirge bleibt der Schnee an den Ästen der älteren Fichten bis zur vollen Sublimation haften, in den Jungbeständen biegen sich die Äste unter der Last der Schneeschicht, und der Schnee fällt herunter. Pulverschnee wird vom Wind verweht. Die Buche hält im Winterzustand nur kleine Schneemengen auf. Die Regenwassermenge, welche von den Buchenkronen herabfließt, ist desto größer je größer die Krone ist. Längs der Buchenstämme fließen große Wassermengen auch bei starker Taubildung (50—100 l Wasser).

Feuchtigkeitsverteilung im Wurzelraum der Holzarten

Die Wassermengen, welche in den Buchen-, Fichten- und Tannenbeständen zum Boden gelangen, sollten sich auch entsprechend in der Bodenfeuchtigkeit bemerkbar machen. Das Ergebnis der Entnahme der Bodenproben und der Kontrolle der momentanen Feuchtigkeitszustände haben gezeigt, daß auf diese Weise nur ein Feuchtigkeitszustand erfaßt werden kann, der durch die kapillare Bodenwasserbewegung hervorgerufen wird. Jene Wassermenge, die durch die Bodenporen, d. h. gravitationsweise in den Boden eindringt, oder längs der Wurzelstränge abfließt, macht sich nicht durch eine volle Benetzung der Bodenschicht geltend und kann daher nicht im Wege der normalen Bodenprobenentnahme festgestellt werden. Die Art der Wasserbewegung im Wurzelraum der Holzarten kann versuchsweise nachgewiesen werden. In einer Entfernung von 0,5—1,0 m vom Stamm wird ein 1,0—2,5 m tiefer, senkrechter Einschnitt hergestellt und ein Teil der Bodenoberfläche (ca. 1 m²) wird in angemessener Entfernung vom Rande des Einschnittes durch einen Kunstregen (50—100 mm in 1 Stunde) bewässert. Im Wurzelraum einer 50jährigen Buche fließt das Wasser nicht oberflächlich ab, aber nach 30—60 Minuten

strömt das Wasser an verschiedenen Stellen aus der Wand des Einschnittes in einer Tiefe von 0,5—2,0 m. Im Wurzelraum einer 60jährigen Fichte fließt das Wasser oberflächlich ab, während aus der Wand des Einschnittes kein Wasser austritt.

Die Pfahl- und Herzwurzeln sowie auch die Kanäle nach den vermoderten Wurzeln sind Bahnen, längs welcher das Regenwasser in den Wurzelraum schnell eindringt. Im Wurzelraum der flachwurzeligen Fichte durchnäßt das Regenwasser eine Bodenschicht von 0,25—0,30 m, welche jedoch einer raschen Verdunstung ausgesetzt ist.

Ähnlich, wie ein wesentlicher Unterschied zwischen den Abflußverhältnissen im bewaldeten und waldlosen Gebiet festgestellt wurde, ist ein wesentlicher Unterschied im Verhalten der Buche und Fichte, insoweit es sich um das Zurückhalten der Niederschlagsmenge im Kronenraum handelt, die in den Beständen zum Boden gelangen; eine grundsätzliche Verschiedenheit ist auch in der Weise, wie diese Holzarten im Wurzelraum das Regenwasser aufnehmen.

Die morphologische Gestaltung der Buche ermöglicht die Erhaltung eines 80-v. H.-Anteils des Niederschlagswassers im flüssigen Zustand für eine weitere biologische oder wasserwirtschaftliche Verwendung. Die Fichte dagegen kann höchstens die Hälfte des Niederschlages, der in ihren Beständen zur Bodenoberfläche gelangt, im flüssigen Zustand erhalten.

Einfluß der Bewirtschaftung der Grundstücke in Quellgebieten auf den Wasserhaushalt

Der länger als 200 Jahre dauernde Unterschied in der Art der Bewirtschaftung der Grundstücke im bewaldeten Gebiet Kychová und in dem landwirtschaftlich genutzten Gebiet Zdechovka führte im letzteren Gebiet nicht nur zur Entwicklung einer sehr schädlichen Erosion an den Abhängen und in den Gerinnen, sondern auch zu weitgehenden Änderungen in den Abflußverhältnissen. Unvorsichtiger Holztransport hat zwar auch im bewaldeten Gebiet eine Geschiebebewegung in Bachgerinnen (in den Jahren 1928—1955, ca. 785 m^3) zur Folge, im waldlosen Gebiet Zdechovka haben jedoch die Hochwässer zur Meßstrecke 6360 m^3 Geschiebe zugeführt. Oft vorkommende hohe Wasserstände an allen Wasserläufen rufen eine sehr intensive Längs- und Quererosion hervor; auch an den Abhängen entstehen infolge des Transportes und der Beweidung tiefe Rinnen, welche mit den Hohlwegen den raschen Abfluß beschleunigen. Jede Erosionsrinne wirkt wie ein Einschnitt, der aus dem breiten Gebiet das Wasser saugt, so heftig, daß in den Trockenperioden nicht nur die Gerinne, sondern auch die Brunnen trocken gelegt werden. Die große Vertiefung des Zdechovkabaches verursacht dauerhafte Rutschbewegungen an beiden Abhängen.

Zusammenfassung

Die Mischbestände von Buchen, Fichten und Tannen im Kychovágebiet haben schon länger als 100 Jahre weder einen schädlichen Regenwasserabfluß, noch einen Rückgang des Wassers in Trockenperioden, wie es im waldlosen Gebiet der Fall ist, verzeichnet. Im Gegenteil, diese Mischbestände erniedrigen die maximalen Hochwasserstände fast auf ein Drittel und den Geschiebetransport auf ein Fünftel der im waldlosen Gebiet gemessenen Mengen. Der ausgeglichene Abfluß im Gerinne zusammen mit dem Wasserleitungsabfluß

aus dem bewaldeten Gebiet ist wesentlich höher als die Wassermengen, die infolge der mächtigen Drainung des ganzen waldlosen Gebietes durch die erodierten Bachgerinne abgeleitet werden. Die Kenntnisse über die Hydrologie der Buche, Fichte und Tanne geben bereits einen Aufschluß über die Ursachen der schädlichen Hochwasserabflüsse im bewaldeten Gebirge. Die Fichte, die eine Hauptholzart im Gebirge ist, hält einen 40-v. H.-Teil der Niederschläge zurück, aber bei größeren Regenmengen ist ihre Retentionsfähigkeit bald erschöpft und es kommt dann zu einem totalen Abfluß. Die seichte Bewurzelung dringt nur in eine Tiefe bis 30 cm ein, aber der Boden wird durch die Wurzelstränge nicht genug fest gebunden, infolgedessen kommt es im Gebirge, das mit Fichten bewachsen ist, zu Rutschungen. Die Speicherung von Grundwasser wird von der Fichte, besonders dort, wo Ortstein entstanden ist, nicht unterstützt. Der wasserwirtschaftliche Wert der Buche besteht darin, daß sie ungefähr 80 v. H. der Niederschläge in den Boden leitet und das Eindringen in die tieferen Bodenschichten ermöglicht. Die Laubholzbestände ermöglichen den Winterniederschlägen einen hemmungslosen Zutritt zur Bodenoberfläche. Die Laubholzarten mit Pfahl- oder Herzwurzeln sind befähigt, das Niederschlagswasser längs der Wurzelstränge in den Bodenraum abzuleiten. Der unterirdische Abfluß verlängert die Dauer des Wasserabflusses. Die Tanne hält in der Krone ca. 20 v. H. der Niederschläge zurück; die Menge des längs des Stammes herabfließenden Wassers ist unwesentlich. Ihre Herzbewurzelung, die im Kychovágebiet in eine Tiefe von 1,60 m reicht, befestigt den Boden und drainiert ihn. Deswegen ist ihre Anwesenheit an den Abhängen im Gebirge vom wasserwirtschaftlichen Standpunkt wesentlich günstiger als die der Fichte.

III. Verwendbarkeit der Holzarten für die Uferbefestigung

Die Forschung der Verwendbarkeit der Laubholzarten für die hydrotechnischen Aufgaben an den Wasserläufen, besonders der Wurzelsysteme, bezog sich vor allem auf Baumholzarten, die an den Uferlinien wachsen. Die untersuchten Sträucher waren nicht alle an den Uferlinien vorhanden, infolgedessen konnten die Beziehungen dieser Holzarten zu den speziellen Standorten, die auch entscheidend sind, nicht kontrolliert werden. Insgesamt wurden 37 Holzarten untersucht; im folgenden werden nur einige angeführt.

a) Laubhölzer

1. Der Bergahorn, Acer pseudoplatanus,

bildet eine sehr dicht verzweigte Herzwurzel; ca. die Hälfte des Wurzelwerkes hat einen schiefen Verlauf nach unten bis unter den Wasserspiegel. Die oberen Wurzelzweige sind ebenso dicht verteilt; einzelne Äste verlaufen nahe der Bodenoberfläche, sind sehr gekrümmt und dicht mit Haarwurzeln bewachsen und besonders in der Uferwand verwachsen. Ein 20jähriger Baum (Höhe 9 m, Bruststärke 14 cm) befestigte die Uferwand auf eine Länge von 3 m, eine Breite von 1,50 m und 1 m tief in den Boden. Ein 30jähriger Baum befestigte mit dem dichten und langen Wurzelwerk eine Uferwand auf eine Länge von 7 m, eine Breite von 1,5 m und eine Tiefe von 1 m. Einzelne Wurzeläste waren bis 7 m lang und stark gekrümmt; die Hauptmasse der Wurzeln ist in der Uferwand entstanden. Abseits vom Baum reichten mehrere Wurzeläste auf eine Entfernung bis 6 m.

Für die Uferbefestigung werden 3—4jährige Heister bis 1,5 m hoch über die Sohle und bis 4 m vom Uferfuß gepflanzt. Im Alter von 10 Jahren kann

der Bergahorn im Reihenverband auf eine Entfernung von 2,0—2,5 m, im Alter von 20 Jahren auf eine Entfernung von 3,0—4,0 m, beziehungsweise in 30 J. 5—7 m weit belassen werden.

2. Der Feldahorn, Acer campestre,

ist ein langsam wachsender Baum des wärmeren Hügellandes, bedeutend ausschlagfähig, empfindlich gegen Verletzung. Er hat eine kurze in 20 J. bis 3 m lange, in 30 J. bis 4 m lange und starke, wenig gekrümmte Wurzel, von welcher sich dünne Äste, dicht mit Haarwurzeln bewachsen, abzweigen. Die Wurzeln wachsen in Lehmbodenbänke und in alte, harte Geschiebeablagerungen ein. In 30 J. befestigt der Baum eine Uferwand in der Länge von 5 m und Breite von 3 m bis 0,80 m tief. In die Uferböschung ist der Feldahorn mit festen, reich verzweigten Ästen verankert.

3—4jährige Pflanzen werden bis 1,5 m hoch über die Sohle und bis 2 m weit vom Uferfuß ausgesetzt. Im Alter von 20 J. kann er im Reihenverband von 3 m belassen werden.

3. Die Weißerle und Schwarzerle, Alnus incana, A. glutinosa

Schnell wachsende Holzarten mit einer starken Ausschlagsfähigkeit, welche Verletzungen und Überschwemmungen gut vertragen. Beide Erlen haben eine kurze, besonders in der Jugend, oberflächliche Bewurzelung. Im Alter von ca. 20 J. ändert sich das Wurzelwerk in der Form eines abschüssigen Kegels. In 10 J. sind einzelne Wurzeläste bis 2,5 m lang, aber die Uferwand wird nur auf eine Länge von 1,5 m, in 20 J. auf eine Länge von 2,5—3,0 m befestigt. Die Wurzeln von Erlen wachsen nicht in Lehmbodenschichten ein.

2—3jährige Pflanzen werden bis 1 m hoch über die Sohle, 1 m vom Uferfuß im Reihenverband von 1 m ausgesetzt. Im Alter von 15 J. und mehr dürfen sie im Verbande von 2,5—3,0 m belassen werden.

4. Die gemeine Esche, Fraxinus excelsior

Sie ist eine Holzart mit dicht verzweigtem, langem, verwachsenem Wurzelwerk, das die Uferwand sehr gut befestigt und weit (bis auf 15 m) in den Boden verankert ist. In der Jugend, solange die Wurzeln nicht genügend Wasser finden, hat die Esche ein langsames Wachstum. In den Feldstrecken der Wasserläufe muß sie des großen Wasserverbrauchs wegen, von den Feldern durch einen bis 0,7 m tiefen Graben isoliert werden. Sie verträgt länger dauernde Überschwemmung, Beschattung und Winterverletzung des Schaftes, aber wiederholte Spätfröste verträgt sie nicht. Im Raume des benetzten Profils wächst die Esche nicht. Die Hauptwurzelmasse ist besonders in der Uferwand dicht entwickelt und reicht in eine Tiefe bis 1 m, wobei einzelne Wurzelzweige an den Enden mit dichten und langen Haarwurzeln bewachsen sind. Einzelne, bis 15 m lange Wurzeläste, die erst am Ende sich fingerartig verzweigen, wachsen abseits vom Baum. Die ausgeprägte Pfahlwurzel reicht bis unter den tiefsten Wasserstand im Wasserlaufe. Die Wurzeläste sind vorwiegend geradlinig und verlaufen parallel zur Oberfläche. Das Gewicht der Wurzelmasse eines 25jährigen Baumes beträgt bis ein Drittel des Gewichtes der oberirdischen Holzmasse. Bei einem 45jährigen Baum (Höhe 17 m, Brustkstärke 28 cm) wurde eine Gesamtlänge von 68 000 m der ganzen Wurzelmasse festgestellt; die Wurzeln nehmen eine eliptische Fläche von einer Achsenlänge von 20 m, bzw. 12 m ein und sind im Boden bis zu einer Tiefe von 1,0 m verwachsen.

Die 3—4jährigen Heisterpflanzen werden im Verband von 1 m bis 2 m hoch über die Sohle und bis 3—5 m weit vom Uferfuß ausgesetzt. Im Alter von 20 J. kann die Esche in einem Verbande von 3—4 m, im Alter von 30 J.

bis 6 m und im Alter von 45 J. bis 10 m belassen werden. Die Eschealleen bilden im Wurzelverbande eine Ufersicherung von sehr hoher Festigkeit.

5. Die Traubenkirsche, Prunus padus

Sie ist eine schnell wachsende Holzart, deren Wurzeln die Fähigkeit besitzen, feste Lehmbodenbänke sowie auch bis 5 cm starke Sandsteinschichten durchzudringen. Sie verträgt nicht Sommerverletzungen, während Frühjahrsüberschwemmungen keine Folgen haben. Ein 20 J. alter Baum befestigt die Uferwand auf eine Länge von 5 m und eine Tiefe von 0,8 m.

Die Traubenkirsche wird als 2—3jähriger Heister bis 1,5 m hoch über die Sohle im Reihenverband von 1 m gepflanzt. Im Alter von 10 J. stabilisiert sie die Ufer auf eine Länge von 2—3 m, in 20 J. auf eine Länge von 4—5 m.

6. Die Schwarzpappel, Populus nigra

ist eine sehr rasch wachsende Holzart von besonders großer Ausschlagsfähigkeit. Die Schwarzpappel verträgt schwere Stammverletzungen, länger dauernde Überschwemmungen sowie auch wiederholte Bedeckung mit Geschiebematerial. Mehr als 50 J. alte Bäume eignen sich nicht mehr für die Uferbefestigung an Wasserläufen mit größerer Wühltätigkeit (geringe Wurzelfestigkeit und eine schwere Baumkrone erhöhen die Gefahr des Windwurfes). Der Baum entwickelt die Hauptwurzelmasse an der Seite der überwiegenden Windrichtung, so daß die Ufer an der Gegenseite nicht durchgewurzelt sind.

In 10 J. befestigt die Schwarzpappel die Ufer auf eine Länge von 3 m, in 20 J. auf eine Länge von 4—5 m und eine Tiefe von 0,5—0,7 m. Die Pflanzung erfolgt durch Setzstangen in der Weise, daß der Basenanteil bis zum Grundwasserspiegel reicht und der Terrainanteil ungefähr 0,5 m oberhalb der Bodenoberfläche verbleibt und zwar im Verband 1—4 m. Sie eignet sich gut für die Befestigung der überschwemmten Geschiebeablagerungen und niederen Ufer.

7. Die Weiß-, Mandel- und Bruchweide, Salix alba, S. amygdalina und S. fragilis

Diese Weiden sind ebenfalls schnellwachsende Bäume mit hervorragender Ausschlagsfähigkeit. Eine Sommerverletzung vertragen die Weiden nicht. In 35—40 J. hört ihre technische Verwendbarkeit auf. Im Alter von 10 J. befestigen die Baumweiden die Böschungen auf eine Länge von 1,5—2,0 m, in 15 J. und später höchstens auf eine Länge von 3 m.

b) Sträucher

1. Der baumförmige Erbsenstrauch, Caragana arborescens

In 5 J. hat sie dichte, gekrümmte, bis 1 m weit und in eine Tiefe von 0,5 m gehende Wurzelzweige, die eine Fläche im Ausmaße von 1,0 × 0,5 m stabilisieren. In 10 J. hat die Caragana auf einer Fläche von 1,5 m² bis 1000 m langes Wurzelwerk; das Gewicht des Strauchs und Wurzelholzes ist im Verhältnis 1 : 2.

2. Der gemeine Blasenstrauch, Colutea arborescens

Ein 5jähriger Strauch hat 3,5—5,0 m lange, nur wenig geteilte Wurzelzweige (ohne Haarwurzeln), die schräg in eine Tiefe von 1,5—1,8 m auslaufen. Ein 10jähriger Strauch hat auf 1 m² ein ca. 220 m langes Wurzelwerk. Das Gewicht des oberirdischen Teiles und der Wurzel ist im Verhältnis 2 : 3. An

sonnigen, kalkhaltigen Böden verbessert der gemeine Blasenstrauch in der Gemeinschaft mit Liguster, gemeinem Schneeball und der schwarzen Heckenkirsche die Festigkeit der Uferlinien.

3. Der gemeine Spindelbaum, Evonymus europea

Der Strauch ist durch eine kleinere Anzahl der Hauptwurzeläste (4—6), die aber dicht verzweigt sind, gekennzeichnet. In 5 J. befestigt er eine Uferfläche 1,0 × 0,8 m bis zu eine Tiefe von 0,3 m (550 m langes Wurzelwerk auf 1 m²), in 10 J. reichen seine Wurzeln bis 1,2 m weit und dringen in eine Tiefe von 0,5 m ein (650 m langes Wurzelwerk auf 1 m²). Das Gewicht der Strauchmasse und der Wurzel ist im Verhältnis bis 1 : 1.

4. Die schwarze Heckenkirsche, Lonicera nigra

Die Wurzeln eines 5jährigen Strauches erreichen eine Länge bis 1,5 m und eine Tiefe bis 0,55 m, die Wurzeln eines 10jährigen Strauches haben eine Länge bis 2,7 m und eine Tiefe bis 0,8 m. Die langen Wurzeln sind dicht mit Haarwurzeln bewachsen. Ein 5 J. alter Strauch befestigt eine Fläche von 1,0 × 1,0 m bis in die Tiefe von 0,4 m. Ein 10jähriger Strauch stabilisiert eine Fläche von 1,5 × 1,2 m und dringt in eine Tiefe von 0,8 m ein.

5. Der Liguster, Ligustrum vulgare

Die Wurzeln eines 5 J. alten Strauches befestigen eine Fläche von 1,0 × 1,2 m bei einer Tiefe von 0,3 m (600 m langes Wurzelwerk auf 1 m²). Ein 10 J. alter Strauch durchwurzelt eine Fläche von 2,0 × 2,0 m bis in die Tiefe von 0,6 m (500 m langes Wurzelwerk auf 1 m²). Die Länge der Wurzel eines 15 J. alten Strauches mißt bis 2,3 m und seine Wurzeln reichen in eine Tiefe von 0,8 m. Das Gewicht des Strauches und der Wurzeln ist im Verhältnis 1 : 2.

6. Die Weiß-, Korb- und Purpurweide, Salix alba, S. viminalis und S. purpurea

Das hervorragende Ausschlagsvermögen der Weidenarten hatte zur Folge, daß außer den Strauchweiden bei den Uferbefestigungen keine anderen Straucharten verwendet wurden. Die Strauchweiden haben sich auch bei der Belebung einfacher Reisig-, Holz- und Steinbauten bewährt, weniger schon bei der Bepflanzung der Uferlinien. Eine Beständigkeit der Weidenspreitlagen ist von der Geschmeidigkeit der Ruten abhängig, die Bewurzelung der Absenker ist verhältnismäßig schwach. Der einjährige Absenker der Purpurweide in der Spreitlage hat nur Haarwurzeln, die 1 mm stark und 6—24 cm lang sind. Ein 4jähriger Absenker (Strauch mit 16 Ruten) ist in der ganzen Länge (1 m) dicht mit 10—50 cm langen Haarwurzeln bewachsen. Außerdem hat ein solcher Absenker 8 längere Wurzeläste (bis 1,5 m lange). Die Gesamtlänge der Wurzeln mißt 275 m. In schattigen Tälern und auf Lehmböden gedeihen die Strauchweiden nicht; auch vertragen sie nicht Verletzungen der Ruten in der Vegetationsperiode.

7. Der gemeine Schneeball, Viburnum opulus

Ein Strauch im Alter von 5 J. durchwurzelt einen Raum von 1,2 m² in eine Tiefe von 0,3 m; auf 1 m² entfallen ca. 580 m Wurzeln. Ein 10jähriger Strauch durchwurzelt einen Raum von 2,0 × 2,0 m in einer Tiefe von 0,6 m und auf 1 m² entfallen ca. 500 m Wurzeln (im ganzen 2100 m). Ein 15jähriger Strauch hat bis 2,3 lange Wurzeln, die in eine Tiefe bis 0,85 m reichen. Auf 1 m² entfallen ca. 600 m Wurzeln.

Zusammenfassung

Wie aus der Beschreibung der Wurzelsysteme einiger Holzarten und ihrer Beziehungen zum fließenden Wasser folgt, sind unter unseren Hölzern solche Arten, die bei der Abwehr gegen Erosion an den Wasserläufen so gute Dienste leisten, daß man sie wirklich nicht durch bautechnische Mittel ersetzen sollte. Ihre Widerstandsfähigkeit, besonders an schotterführenden Wasserläufen, Einfachheit der Anwendung und die billigen Kosten ermöglichen eine rentable Ufersicherung und dauerhaften Schutz gegen die schädliche Ufererosion und gegen die Einwirkungen der Hochwässer an den ganzen Wasserläufen, von der Mündung bis in die Quellstrecken.

Die praktische Anwendung der Erkenntnisse, die aus der Untersuchung der Wurzelwerke gewonnen wurden, bewährte sich bei der Stabilisierung der natürlichen Wasserläufe, die sich durch große Geschiebeführung kennzeichnen (Karpaten, Flysch). Es ist auch gelungen eine planmäßige Ausgleichung der scharfen Krümmungen der Gerinne (mit Hilfe von Buhnenbauten und mit Ausnützung der kinetischen Energie der Hochwässer zur zielbewußten Bildung der Geschiebeablagerungen) zu erzielen und die neugebildeten Uferlinien bloß durch Bepflanzung mit Holzarten zu befestigen.

IV. Schlussfolgerung

Unter unseren Holzgewächsen gibt es solche Arten, mit welchen man in humiden Quellgebieten den Boden an Gebirgshängen drainieren, gleichzeitig aber auch gegen Wassererosion befestigen kann. Solche Maßnahmen sind dazu geeignet die Wasserverdunstung zu vermindern, den Wasservorrat zu schützen, eventuell auch zu vergrößern, bzw. die Uferböschungen gegen Hochwässer zu sichern und die Infiltration des Niederschlagswassers zu beschleunigen. Dieser günstige Einfluß der Holzgewächse auf Boden und Wasser läßt sich durch keine andere rentablere künstliche Einrichtung ersetzen. Es ist aber nicht notwendig ihn zu ersetzen, falls die natürlichen Gewächse bei zweckmäßiger Anwendung wichtige, aber oftmals wegen Kostspieligkeit der technischen Durchführung unterlassene und vergehende Grundaufgaben der Wasserwirtschaft erfüllen können.

In diesen günstigen Einflüssen und Wirkungen äußert sich die mächtige Stärke und Widerstandsfähigkeit dieser festen und dauerhaften Pflanzengebilde, die wirklich befähigt sind, jahrhundertelang nicht nur eigene Lebensbedingungen, sondern auch die Bedürfnisse und Dasein alles Lebendigen in ihrer Umwelt zu schützen. Ein kleinwinziger Samen der Esche ist fähig für seinen Aufbau in 45 Jahren eine Basis im Ausmaße von $20 \times 12 \times 1$ m, vom Gewicht bis 31 Tonnen und mit einem Wurzelwerk in der Länge von 70 000 m auszubilden. Ney hat im Jahre 1894 einen Fall zitiert, wo eine Buche mit einer 80 m^2 großen Kronenfläche während eines Niederschlages von der Größe 57 mm eine Wassermenge von 1200 Liter längs des Schaftes herabgleiten ließ. Aber nicht nur die Esche und Buche, jede von unseren Holzarten ist durch ihre Eigenartigkeit in den Beziehungen zum Boden und Wasser gekennzeichnet. Die Kenntnisse über diese Beziehungen und ihre Anwendung in der Wasserwirtschaft werden dazu beitragen, daß die Hochwassergefahr und auch die Wasserverluste infolge Verdunstung vermindert und demzufolge die Wasserstände in den Wasserläufen und Brunnen in den Trockenperioden gebessert werden können.

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